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DEVELOPMENT OF DESIGN CRITERIA FOR SENSOR DISPLAYS

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Hughes Aircraft Company

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This is the annual report of research conducted under ONR Contract Number N00014-72-C-0451, NR 213-07, entitled Development of Design Criteria for Sensor Display Systems. This report summarizes the work accomplished since the interim report dated June 1973. The following topics are treated in this ~~annual~~ report:

- Psychophysical studies, modulation sensitivity function
- Cognitive demand studies
- Analysis of display mechanization performance criteria.

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FOREWORD

This report presents work which was performed under the Joint Army Navy Aircraft Instrumentation Research (JANAIR) Program, a research and exploratory development program directed by the United States Navy, Office of Naval Research. Special guidance is provided to the program for the Army Electronics Command, the Naval Air Systems Command, and the Office of Naval Research through an organization known as the JANAIR Working Group. The Working Group is currently composed of representatives from the following offices:

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— Avionics Division; Navigation Instrumentation and Display Branch (NAVAIR-53371)
— Crew Systems Division; Cockpit/Cabin Requirements and Standards Branch (NAVAIR-5313)

U.S. Army, Army Electronics Command, Avionics Laboratory, Fort Monmouth, New Jersey
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The Joint Army Navy Aircraft Instrumentation Research Program objective is: To conduct applied research using analytical and experimental investigations for identifying, defining and validating advanced concepts which may be applied to future, improved Naval and Army aircraft instrumentation systems. This includes sensing elements, data processors, displays, controls and man/machine interfaces for fixed and rotary wing aircraft for all flight regimes.

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Messrs W. C. Hoffman, J. L. Heard, and E. Dragavon contributed the section on display mechanization. Ms. J. Herman very patiently conducted the laboratory research and analyzed the results. Special acknowledgement is paid to CMDR G. Smith who served as Scientific Officer during this phase of the research program, and to the members of the JANAIR Committee, in particular Messrs. J. Wolin and S. Merriman for their technical guidance and assistance.

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1.0 INTRODUCTION

Sensor displays for air-to-ground weapon delivery missions are used by the crew to find, recognize, and locate targets or landmarks. The display designer is charged with selecting, within the framework of physical and cost constraints, those display characteristics that enhance the crew's performance of those tasks. If the designer is to evaluate candidate display configurations intelligently, he must be provided with data which informs him of the crew's performance that may be expected to accompany design variations. In particular, he wants to know the sensitivity of crew performance to candidate design variations. In the absence of any firm knowledge of how those design options affect operator performance, the display designer typically will design a display system to reproduce the highest frequency information gathered by the sensor.

At the same time, consideration will be taken of those display characteristics that are known, through an established lore, to have a marked effect on image quality and display visibility. Included in these considerations are:

- Refresh rate
- Persistence
- Jitter
- Uniformity
- Luminance
- Dynamic range
- Modulation transfer function
- Filters
- Color.

Seldom, however, are the cognitive needs of the operator taken into account. This is partly because those needs are primarily related to the sensor characteristics rather than the display design and partly because those needs are not well understood. The cognitive needs of the operator are satisfied by the characteristics of the sensor/display system that permit the operator to extract information from the displayed image about the sensed object space. These needs differ according to the operator's task but will include:

- Definition (number of line pairs per object)
- Coverage or field of view
- Brightness transfer function
- Storage (temporal).

The intent of this program is to develop functional display design criteria based on the relationship between design characteristics and operator performance. In order to develop such criteria one must:

- Establish the boundaries of the operator's working environment
- Establish the tasks required of the crew
- Bound the sensor types and sensor characteristics of interest
- Establish the operator visual demand characteristics
- Establish the operator cognitive demand characteristics.

The structure to accomplish the program elements is illustrated in Figure 1-1. The tasks indicated by hatching were analyzed during the first year of the program, and the progress achieved was reported in the June 1973 interim report. As a result of these analyses, it was found that the existing data bank with regard to the operator visual demand characteristics was inadequate, and laboratory research to develop more suitable psychophysical data was undertaken during the current report period. The results of these laboratory studies reported in this volume are a description of the modulation sensitivity function of the eye as a function of display luminance, spatial frequency, image size, pattern type, and ambient adaptation level. These data are used to formulate design criteria for display MTF, luminance, and dynamic range.

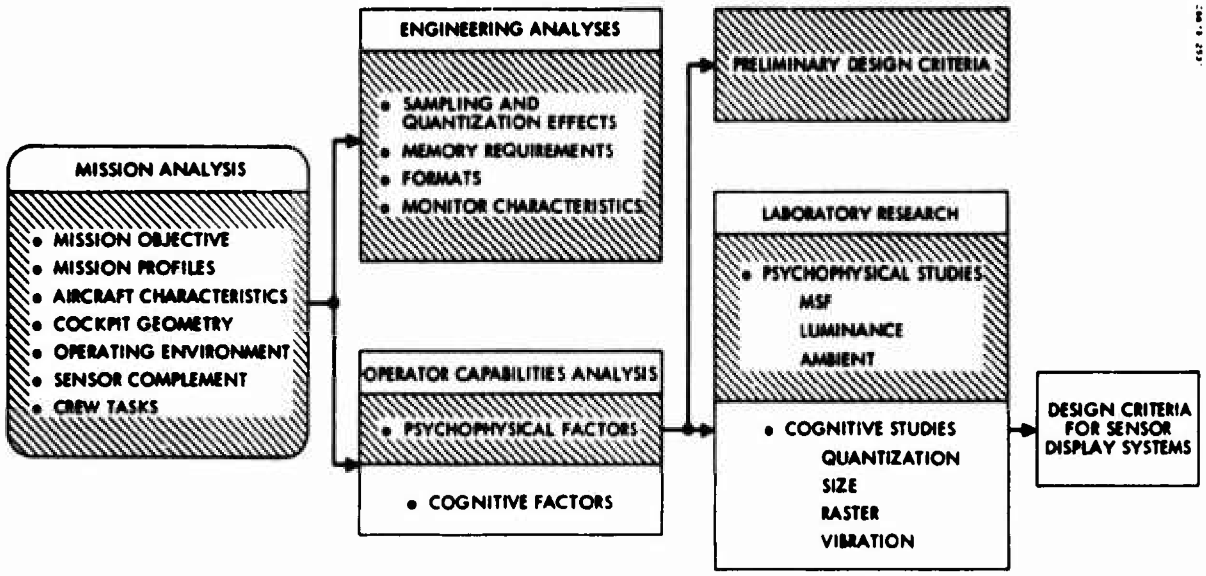

Figure 1-1. Elements in the development of sensor display criteria.

The problem of display design criteria has been compounded by new technologies that involve quantized sampled data systems, e.g. those using digital scan conversion or discrete matrix display devices. Design criteria development for this class of systems necessitates the analysis of the sampling requirements needed to reproduce the sensor input signal and the effects of sampling on operator performance. The major portion of this report addresses problems associated with this class of systems.

An analysis of the effects of spatial and intensity sampling on the reproduction of video information was conducted and is reported in this volume. Along with the formal analyses, two small research studies of the effect of quantization on finding and recognizing targets were carried out. These studies employed two kinds of imagery; radar and electro-optical, and two kinds of operator tasks; finding prebriefed stationary targets or landmarks (radar) and classifying different types of vehicles (electro-optical). The performance data are being used in sensitivity analyses to develop design critiera.

2.0 PSYCHOPHYSICAL STUDIES, MODULATION SENSITIVITY FUNCTION

2.1 BACKGROUND

It was not until the late 1960's that evidence was found showing that visual response to complex spatial waveforms could be closely approximated by Fourier analysis, leading to the concept of the modulation sensitivity function (MSF) as a psychophysical analogue to the optical engineer's modulation transfer function (MTF).* Studies purporting to measure the human MSF proliferated over the next couple of years; yet as will be seen, the problems faced by an operator in the detection or recognition of complex targets within a larger display were not directly addressed and are not accessible through extrapolation from the work that was done.

Figure 2-1 shows two of the most recent MSF determinations plotted with the Patel (1966) data which has become somewhat of an industry standard.

It is possible to predict the recognizability of a target from MSF curves, using definition criteria such as the Johnson (1958) data. If a certain number of raster lines must be laid across a target to achieve recognition, for instance, then it follows that the minimum spatial frequency which must be resolved by the eye is inversely determined by target subtense. This relationship is shown in Table II-1, where the spatial frequencies corresponding to the listed target subtenses (heights in minutes of arc) are

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*Modulation refers to image contrast. It is defined at the absolute value of the luminance difference divided by the luminance sum:

$$M = \frac{|b_{max} - b_{min}|}{b_{max} + b_{min}}$$

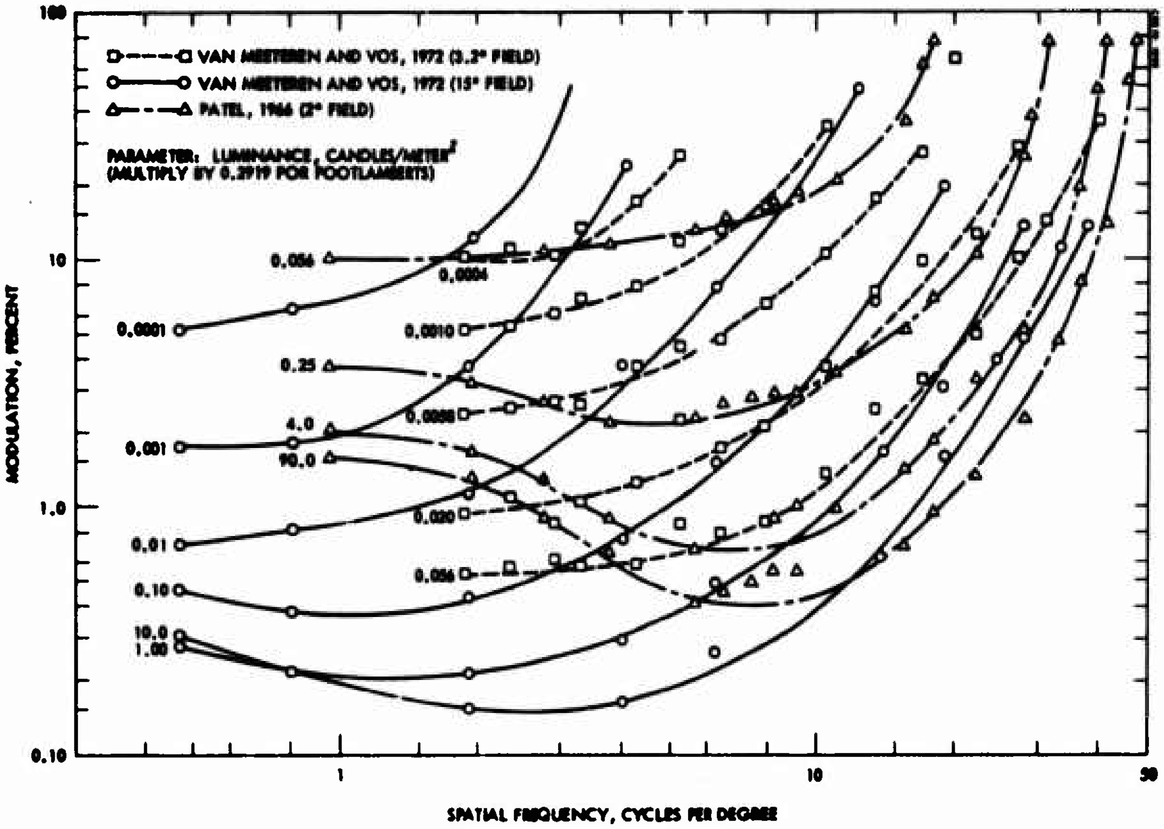


Figure 2-1. Three versions of the modulation sensitivity function.

TABLE II-1. RELATIONSHIP OF TARGET SUBTENSE TO SPATIAL FREQUENCY FOR EIGHT-LINE RECOGNITION CRITERION

Target Height	Required Visual Spatial Frequency, cycles/degree
2'	225
4'	112.5
8'	56.25
16'	28.13
32'	14.06
1^{o}	7.5
2^{o}	3.75
4^{o}	1.88

given for the case that eight line pairs must be perceived within the target dimension for recognition. It is clear that the detail structure of 2-minute and 4-minute size targets are beyond the resolution limit of the eye; the eight lines within the detail structure of 8-minute size targets may be resolved only under the brightest conditions with nearly infinite contrast. The remaining target sizes fall within the limits of visibility as defined by the MSF thresholds.

But, referring again to Figure 2-1, it can be seen that the MSF threshold functions are different for different size visual fields. The differences, taken at one of the luminance values that can be found on all three sets of curves, have been plotted in Figure 2-2. The curves follow a smooth function with respect to field size. In this figure, a fourth set of points has been added from a similar study (Van Nes and Bouman, 1967) to show that there does appear to be continuity in this regard. Unfortunately, the region of greatest interest for target recognition — 8 minutes to 2 degrees as seen in Table II-1 — is outside the region covered by the published research summarized in Figure 2-2.

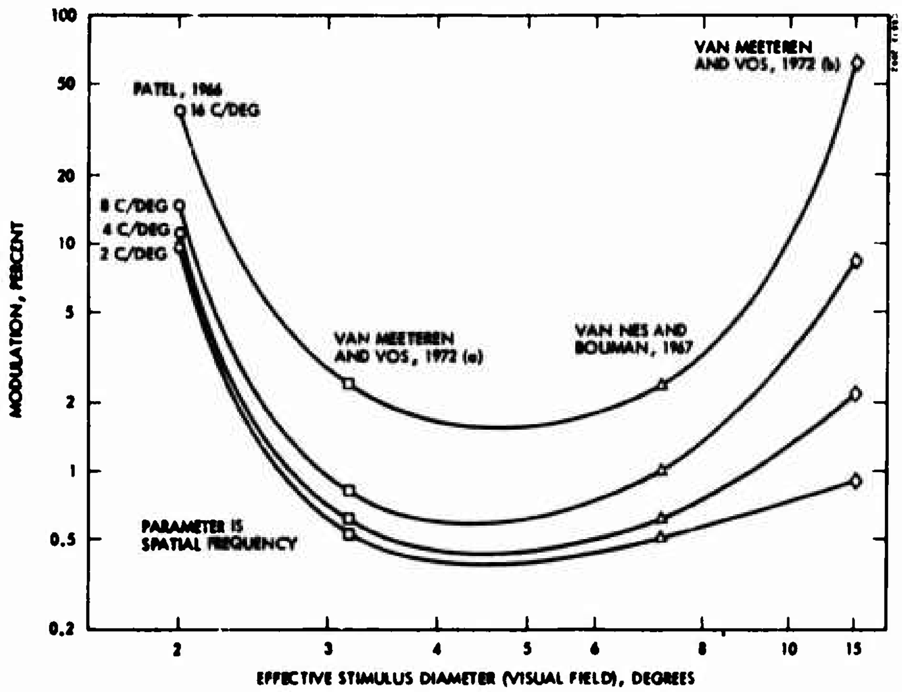


Figure 2-2. Modulation thresholds related to stimulus size at four spatial frequencies (luminance is approximately 0.1 cd/m^2).

2.2 EXPERIMENTAL STUDY

The first impression one receives from summaries such as that in Figure 2-1 is one of substantial disarray in research results bearing on visual perception. The process of piecing together several disparate researches, each performed under different conditions with unique sets of unknowns, can support only the most tenuous conclusions. More is required for the generation of design criteria which can be employed with any degree of confidence.

There are other serious failings in the present data base. For one thing, airborne display systems require much higher luminance than is dealt with in the MSF literature. For another, the interest is not in the visibility of specialized laboratory stimuli such as sinusoidal gratings but in the visibility of mission-critical targets. Therefore one needs to know how to translate laboratory results into predictions of field performance.

The study herein described was designed to resolve some of these shortcomings. The following areas in particular were addressed:

- Examine the combined values of stimulus subtense and spatial frequency which are of importance in target detection and recognition.
- Extend the luminance range of the investigation to realistic values typified by aircraft requirements.
- Assess the effects of simultaneous contrast and misadaptation by including surround luminance as an independent variable.
- Validate the generalizability of the sinusoidal grating through use of an alternate stimulus. A sinusoidal pattern which varies simultaneously in the horizontal and vertical dimensions was selected for this purpose.

2.2.1 Experimental Variables

Five major variables were selected for study under the psychophysical research phase of the Sensor Display program. These variables were stimulus luminance, surround luminance, stimulus subtense, spatial frequency, and modulation type.

Test Stimulus

Sinusoidal stimuli have seen increasing use as visual stimuli over recent years, due principally to a growing body of research (e.g., Campbell and Robson, 1968) which indicates that visual response to complex spatial waveforms may be closely approximated by the sum of responses to sinusoids derived from the complex waveform by Fourier synthesis. Additionally, definition of the visual response in terms of sinusoidal inputs, resulting in a psychophysical version of the modulation transfer function (MTF) called the modulation sensitivity function (MSF) is particularly useful to the engineer, who can multiply other component MTFs by the visual MSF to obtain an overall system MTF for use in display design. It was for these reasons that sinusoidal stimuli were selected for this portion of the research program.

Stimulus Luminance

A major purpose of the study was to extend the range of luminances over which contrast thresholds have been measured. A high-brightness cathode-ray tube was therefore procured and installed in the experimental apparatus. The display was capable of a maximum of 3425 cd/m^2 (1000 foot-lamberts).

Surround Luminance

It is known that the surround luminance can control the visual adaptation level of the observer. If this level is markedly different than the average luminance of the display — as it often is in an airborne environment — the modulation response of the observer may be affected. This variable was included to assess the effect of such adaptation mismatches.

Stimulus Subtense

Stimulus size was included in the experimental factors in accordance with the analysis presented above. Choice of size range was limited at the high end by cathode-ray tubes capable of yielding the high brightness required by the study, and at the low end by the range of spatial frequencies to be investigated. If the stimulus size were so small that only a fraction of a wavelength was visible to the subject, the likelihood of detecting the presence of the waveform would be reduced. Two cycles were selected as the smallest number of wavelengths to be presented to the observer. This meant that the product of stimulus size (measured in degrees of visual angle at the viewing position) and spatial frequency (measured in cycles per degree at the viewing position) could be no less than 2.

Spatial Frequency

The range of spatial frequencies has been well defined by prior research. Resolution of patterns at frequencies higher than 40 cycles per degree quickly exceeds the theoretical limits imposed by the spacing of retinal receptors within the fovea. At the low end, there is little visual information to be found in frequencies less than 3 or 4 cycles per degree. Although some investigators have studied contrast thresholds at lower frequencies, 4 cycles per degree was selected as the lower limit in order to facilitate the use of stimulus sizes as small as 15 arcminutes visual subtense.

Modulation Type

No research has been published on the ability to perceive a pattern which has been modulated in both the horizontal and vertical axes. Because of the known capacity of the visual system to perform spatial integration over a significant portion of the retinal image, it would appear that lower contrast thresholds might obtain for an image which facilitated integration over the vertical dimension by presenting vertically oriented bars. Consequently, it was decided to include a second pattern in which the vertical bars were broken up, again in conformity with a sinusoidal modulation function. It was felt that this sinusoidal patchwork would more closely approximate the hodgepodge of stimuli present in the real sensor world.

Values Selected

The foregoing set forth some of the logic behind the selection of experimental variables. Several pilot studies were performed in order to make preliminary judgments of the relative importance of variables, and to eliminate values, or combinations of values among the several variables, which failed to yield a response or which were trivially easy to respond. The final experimental factors and their values are as follows:

Stimulus Luminance: 0.3, 3, 30, 300, and 2400 cd/m^2 (0.0876, 0.876, 8.76, 87.6 and 700 foot-lamberts)

Surround Luminance: 0.3, 3, 30, 300 and 2400 cd/m^2

Stimulus Subtense: 15', 30', 1°, 2° and 4° visual angle

Spatial Frequency: 4, 6-3/4, 11-3/4, 18-3/4 and 31-1/4 cycles per degree

Modulation Type: Horizontal only (vertically oriented sinusoidal grating) and horizontal and vertical (patchwork).

2.2.2 Method

Apparatus

A high-brightness cathode-ray tube was mounted in a standard 525-line television monitor chassis. Because of the importance of average display luminance, all bias, acceleration, and focusing potentials were obtained from an external regulated power source whose output was continuously monitored with a digital voltmeter.

Modulation waveforms were provided by a function generator whose time base was synchronized to the television monitor horizontal sweep oscillator. For the portions of the study calling for concurrent horizontal-vertical spatial modulation, the basic sinusoid yielding horizontal-only modulation (vertically-oriented sine wave gratings) was multiplied by a second signal bearing the same frequency relationship to the vertical sweep rate. Figures 2-3 through 2-6 show the images viewed by the subjects. Figures 2-3 and 2-4 illustrate horizontal-only modulation at low and high spatial frequencies respectively; Figures 2-5 and 2-6 show combined horizontal-vertical modulation.

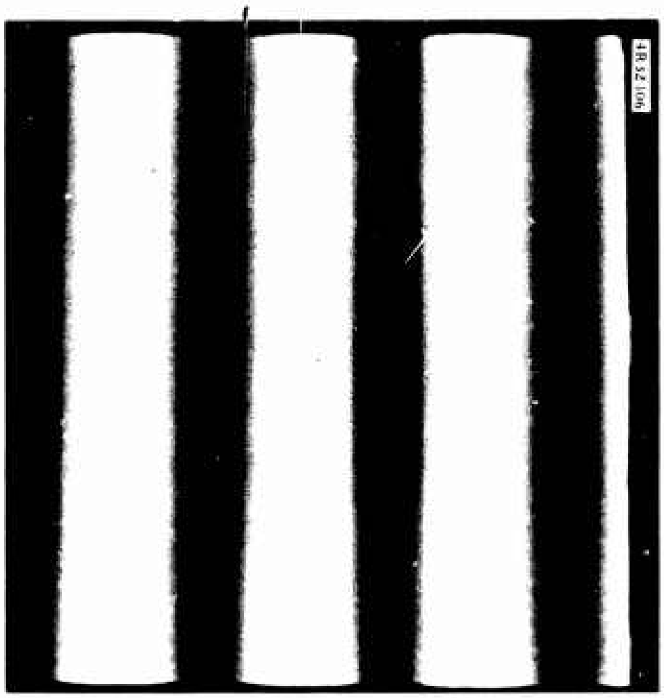


Figure 2-3. Low frequency vertically oriented sinusoidal grating stimulus used in psychophysical study. Grating is shown at high contrast for visibility; actual laboratory gratings were viewed at threshold contrast.

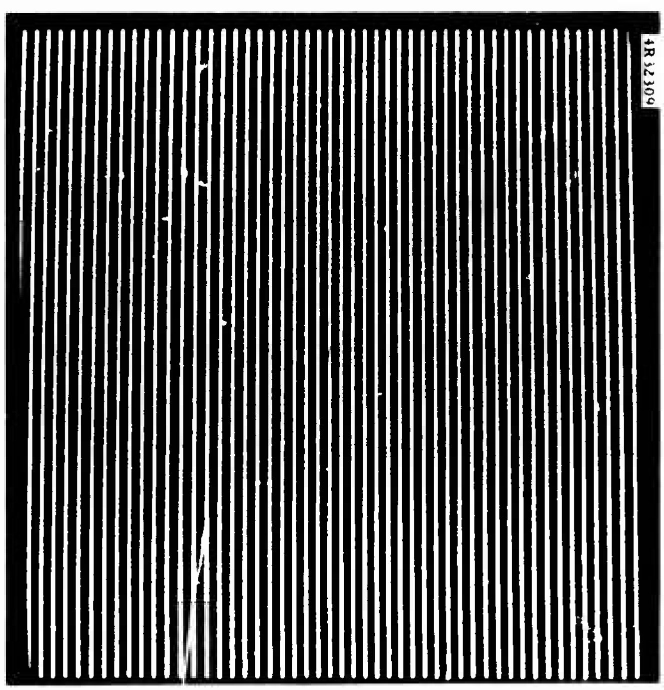


Figure 2-4. High frequency vertically oriented sinusoidal grating stimulus.

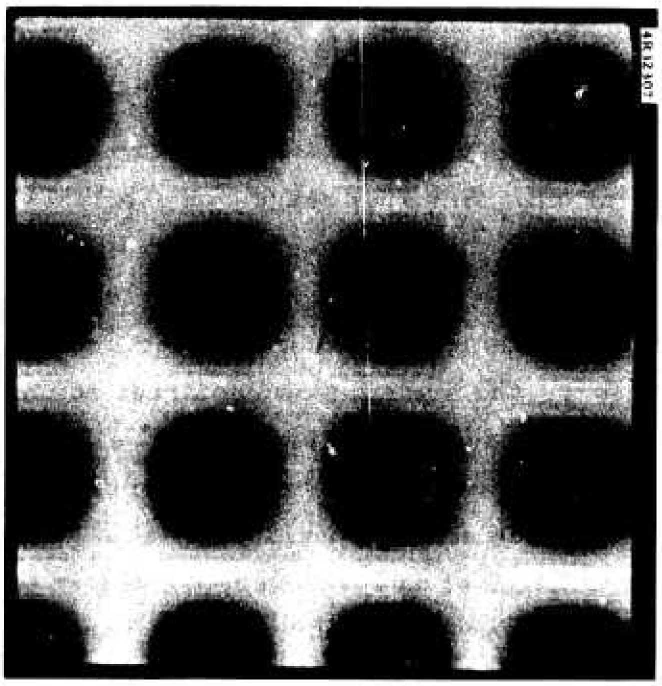


Figure 2-5. Low frequency concurrently modulated grating stimulus. Luminance varies as the sine of distance in both the horizontal and vertical directions.

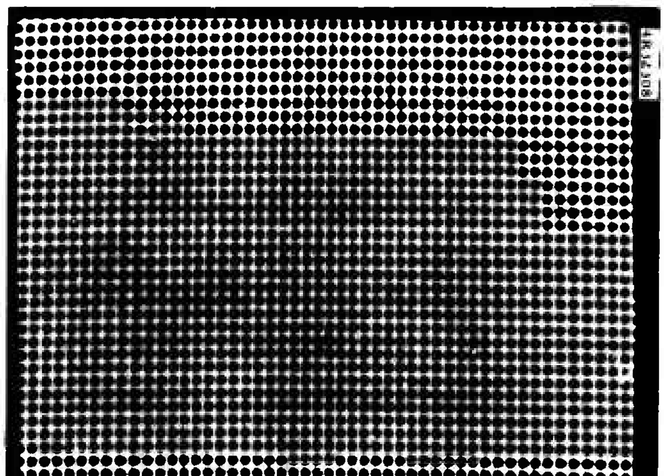


Figure 2-6. High frequency concurrently modulated grating stimulus.

Three modulation attenuation functions were recorded during the course of the experiment. A coarse range was available from a 10-20-30-40-dB attenuator built into the function generator. Calibration of this was verified photometrically for all experimental frequencies, using a Gamma Scientific Model 2000 photometer with a slit aperture. Fine control was provided to the subject, who made his own contrast adjustments with a 10-turn laboratory potentiometer. A calibration curve for converting potentiometer settings into decibels attenuation was also derived photometrically at the screen. Finally, modulation measurements at a standard control setting taken at the start and finish of each run were converted to decibel equivalents against a calibration standard. The sum of these three was recorded for each trial and subsequently changed to log modulation for computation of display modulation.

Display luminance in the absence of modulation was set at 300 cd/m^2 (87.6 fL), using a Spectra Pritchard photometer calibrated to a 100-fL laboratory source. All lower luminances were achieved by placing Wratten neutral density gelatin filters between subject and display, obviating the need to adjust and recalibrate the monitor during most of the experiment. The exception was the 2400 cd/m^2 (700 fL), condition which necessitated separate calibration.

A series of 3 foot by 4 foot white masks provided both the variable display aperture and the uniform surround field. Central cutouts of 5/16-, 5/8-, 1-1/4-, 2-1/2- and 5-inches square subtended the desired visual angles at the viewing position. The masks were placed 2 inches forward of the cathode-ray tube so that the offset surround lighting did not fall on the phosphor surface. A group of floodlights illuminated the masks and were preset to each required value before each run, and then switched on as needed. The Pritchard photometer was used for these adjustments.

The three subjects, employees of the Hughes Aircraft Company, were each 26 years of age, male, and possessed of 20-20 emmetropic vision as verified with a Bausch and Lomb Orthorater*. They were seated

*Registered trademark, Bausch and Lomb.

so that the head could be placed comfortably in an adjustable chin-head support which had been set for a 71.5-inch viewing distance, measured from the display surface to the external canthus.

Psychophysical Method

It is customary to report the results of visual studies in terms of thresholds – that is, the combination of luminance, contrast, spatial frequency and the like which yields responses 50 percent of the time. The two most common psychophysical techniques are the method of constant stimuli (also called the method of limits) and the method of adjustment (Guilford, 1954). With the method of constant stimuli, subjects are presented with a range of experimental conditions above and below the expected threshold, and the proportion of detections is plotted against the experimental variable. From the resulting ogive, the 50 percent threshold is determined. With the method of adjustment, subjects are provided direct control over the stimulus magnitude and instructed to adjust the stimulus to what they believe to be the threshold of seeing. The latter has been shown to be as dependable as the former and has the advantage of requiring fewer trials and less subject time.

Blackwell (1971) has noted that the method of adjustment yields higher thresholds than the method of constant stimuli by a multiplicative factor of from 1.20 to 2.40, depending on observer experience (the lower value corresponding to greater experience). Guth and McNelis (1968) report a multiplier of 1.69 for their experienced observers; as this is approximately the geometric mean of Blackwell's range, it is probably a dependable value.

Inasmuch as the method of adjustment has been shown to produce thresholds at contrasts approximately 1.69 times higher than the method of constant stimuli, it follows that use of the former psychophysical method will yield data that is directly applicable to design with a minimum of experimental effort and subject time. The method of adjustment was therefore used. In addition to the threshold, a second set of measurements was taken corresponding to the observer's judgment of a "comfortable" or "easily visible" stimulus.

Experimental Design and Statistical Analysis

With a multivariate experiment, it is convenient to think of the experimental volume as a hyperspace having as many dimensions as there are factors in the experiment. Within this volume, there are many combinations of the individual factors which combine to yield the same response. If the processes which relate the response to the factors are continuous and possess finite derivatives within the hyperspace, then the set of factor levels which generate a specified response may be thought of as a surface within the experimental volume.

If these surfaces are to be more than a mental exercise, they must be amenable to generation by a reasonably simple mathematical model, whose parameters can then be ascertained by experiment in order to define the response surfaces themselves. Two constraints to this model are that the parameters must be linear and continuous within the experimental volume. A model which satisfies these constraints and which has been previously shown to be capable of representing visual phenomena to a high degree of accuracy is a polynomial equation of the second degree, in which the variables are logarithmic transforms of the original factor levels. By restricting the model to an equation of the second degree, the further constraint that the second derivative be constant within the hyperspace is imposed, i.e., the rate of change of the resulting function must be monotonic and there can be only one inflection. Not only is this restriction reasonable in light of existing research; but a possible failure of the experimental results to conform with it would be immediately apparent in the statistical analysis.

The advantage of defining response surfaces in design-oriented research enables the user to proceed backwards from the response required by his system design to any combination of factor levels capable of yielding that response.

The above may be restated to impose a final constraint on the experimental design — the factor levels must be selected such that the expected average of the squared difference between the model and the experimental data is minimized throughout the experimental volume. This constraint may be realized by assuming that the volume can be described by a hypersphere and computing factor levels by the methods of matrix calculus. Selection of factor levels according to these principles results in what is known as a "rotatable central composite" design (Simon, 1971).

Four of the factors of the present experiment — stimulus luminance, surround luminance, stimulus size, and spatial frequency — were continuous and hence amenable to a rotatable design; their levels were selected according to the preceding logic. The two remaining factors — modulation type and threshold/comfort adjustment — were dichotomous and could not be treated in this fashion. Embedded within the hypersphere of experimental points is a hypercube comprising a 2^k factorial,in this case a 2^4 factorial consisting of the four continuous factors. Expansion of the basic design by increasing this to a 2^6 factorial which included the remaining two dichotomous factors, was straightforward and permitted their inclusion in an overall experimental design as illustrated in Figure 2-7.

Statistical analysis of the results comprised: (1) calculation of the coefficients of the second degree polynomial by means of multiple linear regression, and (2) analysis of variance, by which estimates could be made of the probable error resulting from the derived equation. A stepwise regression technique was adopted which permitted estimation of the probable error arising from the suppression of factors or factor combinations which appear to contribute little to the final outcome.

Procedure

Subjects were instructed verbally (see Appendix A) and given four training trials prior to starting each experimental session. Each of the subjects received three blocks of trials in a different order and started with a different block in each case. The order of trials within blocks was not varied. As is customary with visual research, it was assumed that the effects of learning and transfer would be insignificant in comparison to dark and light adaptation affects between trials. Conditions were therefore ordered in such a manner that adaptation requirements were minimized in

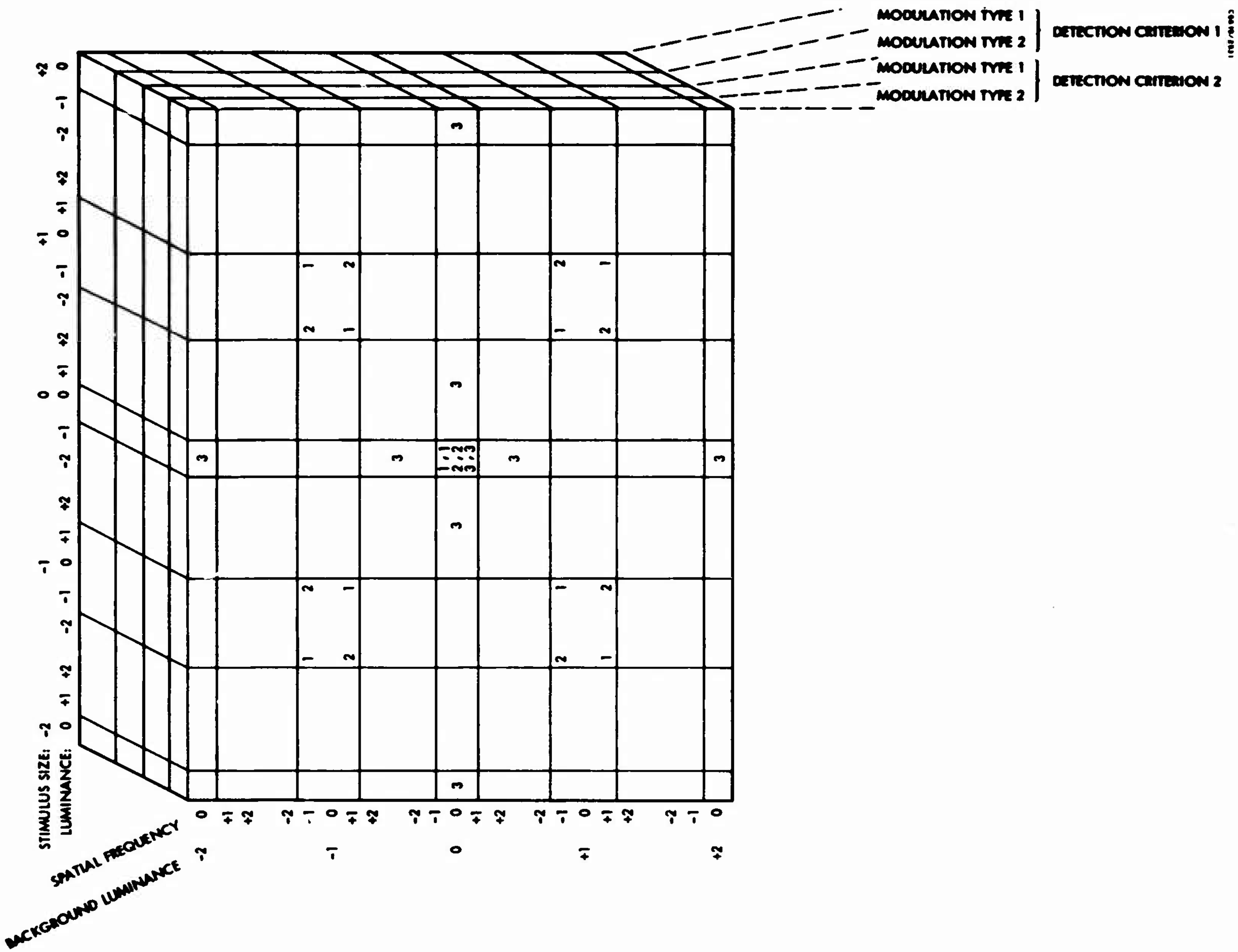


Figure 2-7. Diagram of experimental design. (Marginal entries are coded values of factor levels. Table entries 1, 2, and 3 refer to block numbers. Blocks are orthogonal and each comprises a central composite design of itself.)

both directions. Where a major change in luminace was unavoidable, several minutes were allowed for adaptation before proceeding.

Two modulation settings were made by each subject for each study condition, and both were recorded. Prior to one of the two settings, the experimenter displaced the control in a positive direction, so that the criterion level was approached from an easily visible, high-contrast condition; the second setting was made from the negative (low contrast) direction. The high-low order was not formally randomized, but was varied arbitrarily by the experimenter. Subjects were given a short rest break between blocks. Each block required about 90 minutes to complete.

2.2.3 Results

Two regression analyses were performed. In the first, the Threshold/Comfort criterion was coded as a dummy variable having assigned values of +1 and -1, in order that its effect on the regression equation could be determined. That effect proved to be 1.6 times increase in modulation settings for all conditions. These settings represent contrasts behond the 99th percentile probability. A second regression was performed with this variable suppressed, and subsequent calculations and analyses were made from the threshold data subset. These results will be discussed under the headings of the individual factors.

Modulation Type

Table II-2 shows the analysis of variance for the 2^5 factorial including Modulation Type and the four principle variables. Because use of the method of adjustment with subsequent settings made in opposite directions tends to inflate the replication sum of squares, replications were averaged and experimental effects were tested against the pooled mean square deviations of the higher order interactions. As the table shows, variability attributable to Modulation Type was actually less than expected from chance alone. This factor was therefore not considered further in the data analysis.

TABLE II-2. ANALYSIS OF VARIANCE SUMMARY

Variable	SS/MS	F	P	ETA
A. Stimulus Luminance	184.32	169.82	0.01	0.46
B. Background Luminance	5.28	4.86	0.05	0.01
C. Stimulus Size	24.85	22.89	0.01	0.06
D. Spatial Frequency	117.05	107.84	0.01	0.29
E. Modulation Type	0.35	0.32	--	--
AB.	35.28	32.50	0.01	0.09
AC.	0.18	--		
AD.	2.53	2.33		0.01
AE.	0.00	--		
BC.	0.45	--		
BD.	1.13	1.04		
BE.	0.08	--		
CD.	10.58	9.75	0.01	0.03
CE.	0.01	--		
DE.	0.03	--		
Pooled Higher Order (16 df):	1.09			0.04
MS:	1.09			
Total	399.49			

Two conclusions may be drawn from the nonsignificance of modulation type. The first and most obvious is that no spatial integration within the retina operates to lower perceptual thresholds for images comprised of straight-line gratings over those whose straight contours have been broken up. More important to the present task, there is justification in these results for extrapolating data obtained with sinewave grating stimuli to the solution of real-world visual problems. It is important to be able to expect with some confidence that results obtained under laboratory conditions have a counterpart in the field.

Regression Coefficients and Analysis of Variance

Equations describing the experimental space were developed using a stepwise multiple regression program (UCLA Biomedical Computer Program No. BMD-02R). This program selects variables in order of their partial correlation with the ordinate value, resulting in a series of steps containing increasing numbers of variables roughly in the order of their importance to the overall result. Each step adds to the preceding step that variable which most increases the multiple correlation coefficient and simultaneously removes any variable whose impact, due to intercorrelation, is rendered insignificant by the new addition. The decision is based on computation of Fisher's f statistic.

Three steps were selected as representative of (1) a quick approximation to the experimental results having only six terms but accounting for 80 percent of the variability; (2) a more accurate expression in which each term is statistically significant; and (3) the entire regression equation, which is the best least-squares fit to these data. Table II-3 shows the coefficients of multiple linear regression calculated after Step 5, Step 7, and Step 14 (the complete analysis). The use to which each of these calculations has been put will be explained subsequently.

The analysis of variance for Step 14 is given in Table II-4. The multiple correlation coefficient at this point is 0.9637, showing that approximately 7.13 percent of the variability of the data remains unaccounted for. This is an acceptable figure, inasmuch as between-subject variability is included in that estimate.

Response Surface

A generalized response surface, showing the overall results of the experiment, is shown in Figure 2-8. The dependent variable is modulation sensitivity, defined as the reciprocal of the modulation at which threshold settings were determined. The surface shown is for the median condition of stimulus and surround luminance (30 cd/m^2); other luminance surfaces exhibit the same general form, either above or below the one depicted. The interaction of stimulus size with spatial frequency is clear in the figure.

TABLE II-3. COEFFICIENTS OF MULTIPLE REGRESSION CALCULATED AFTER STEPS 5, 7 AND 14

Variable	Step 5	Step 7	Step 14
A. Log Stimulus Luminance*	-0.64552	-0.51347	-0.31800
B. Log Surround Luminance*			0.12219
C. Log Stimulus Subtense	-0.41392	-0.43732	-1.62162
D. Log Spatial Frequency		-3.33707	-3.05375
A^2.	0.13610	0.15254	0.15041
B^2.	0.06370	0.13097	0.10692
C^2.			0.02441
D^2.	0.73964	2.31010	2.26564
AB.		-0.17248	-0.19435
AC.			-0.01115
AD.			-0.16251
BC.			-0.10949
BD.			-0.03871
CD.			1.24461
Constant Term	-2.12290	-0.52522	-0.81120
Multiple Correlation Coefficient	0.9103	0.9538	0.9637
Squared Correlation Coefficient	0.8286	0.9097	0.9287

*Foot-Lamberts

TABLE II-4. ANALYSIS OF VARIANCE FOR THE COMPLETE REGRESSION

	df	Sum of Squares	Mean Square	f
Due to Regression:	14	53.029	3.788	153.7
Due to Variations About Regression (Residual):	165	4.067	0.025	

Variable	F to Remove	P
A. Log Stimulus Luminance	14.86	0.01
B. Log Surround Luminance	2.62	0.25
C. Log Stimulus Size	37.54	0.01
D. Log Spatial Frequency	35.20	0.01
A^2.	135.72	0.01
B^2.	74.56	0.01
C^2.	---	
D^2.	82.92	0.01
AB.	146.80	0.01
AC.	---	
AD.	5.06	0.05
BC.	4.23	0.05
BD	---	
CD.	26.93	0.01

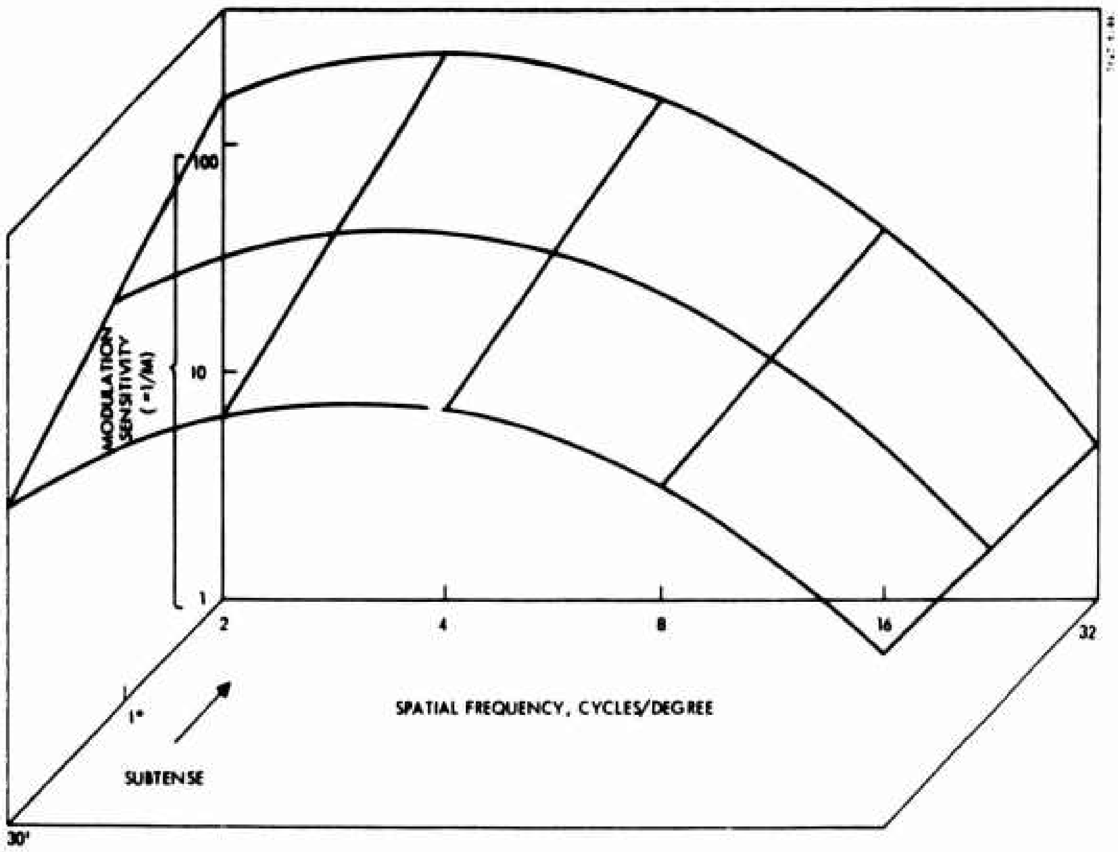


Figure 2-8. Modulation sensitivity as a function of spatial frequency and stimulus size, generalized response to experimental values.

It is also clear that the experiment did not elicit an optimum stimulus size, inasmuch as response is still rising at the boundary in the size dimension. The degradation in response with decreasing size is apparent, however, and will be addressed in greater detail below.

Another composite of the overall results is given in Figure 2-9. This figure shows the effect on the modulation threshold of moving each of the four continuous variables through the experimental space while holding the remaining three constant at the median value. In order that they may all be represented on the same graph, the threshold is plotted against the coded values of the variables, rather than against the physical values. Because the abscissae are different in each case, the limiting values of each function are given in the figure.

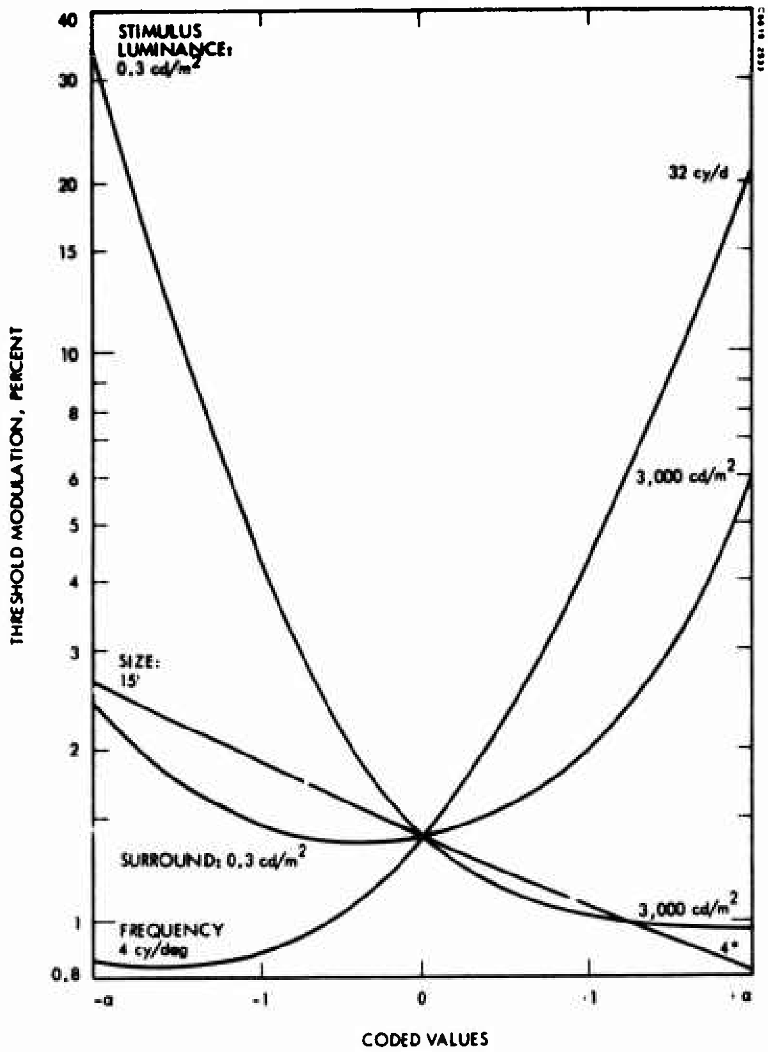


Figure 2-9. Threshold modulation values for each experimental variable separately. Each response function is plotted with the remaining variables held at their median value. Use of coded values permits simultaneous representation of entire experimental volume.

Stimulus Size (Angular Subtense)

Figure 2-10 shows a typical size-frequency function, plotted for stimulus and surround luminances of 300 cd/m^2 and spatial frequencies of 6-3/4, 11-1/4 and 18-3/4 cycles per degree. The significant effect of stimulus size on the visibility of low spatial frequencies is apparent, as is

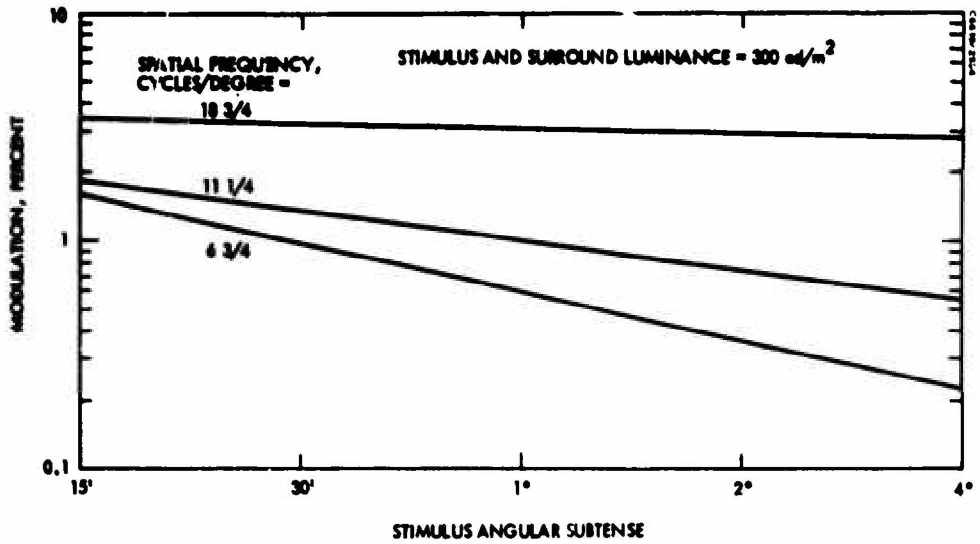


Figure 2-10. Average modulation thresholds as a function of stimulus angular subtense. Spatial frequency is the parameter.

the fact that the visibility of frequencies in excess of 18 cycles per degree is scarcely affected. These data may be given an intuitive calibration by reflecting that the Snellen "E" requires the resolution of 15 cycles per degree when it subtends the handbook-recommended minimum visual angle of 10 minutes. At the lowest perceptible eyechart level for 20-20 vision, 30 cycles per degree must be resolved by the viewer.

Stimulus Luminance

Figures 2-11 and 2-12 show the effects of stimulus luminance on the modulation response function with surround luminance held at the median value of 30 cd/m^2 (8.76 foot-lamberts); Figure 2-11 is for a stimulus subtending 30 arcminutes and Figure 2-12 is for one subtending 2 degrees. The most interesting feature of these plots is the "foldover" effect occurring at the

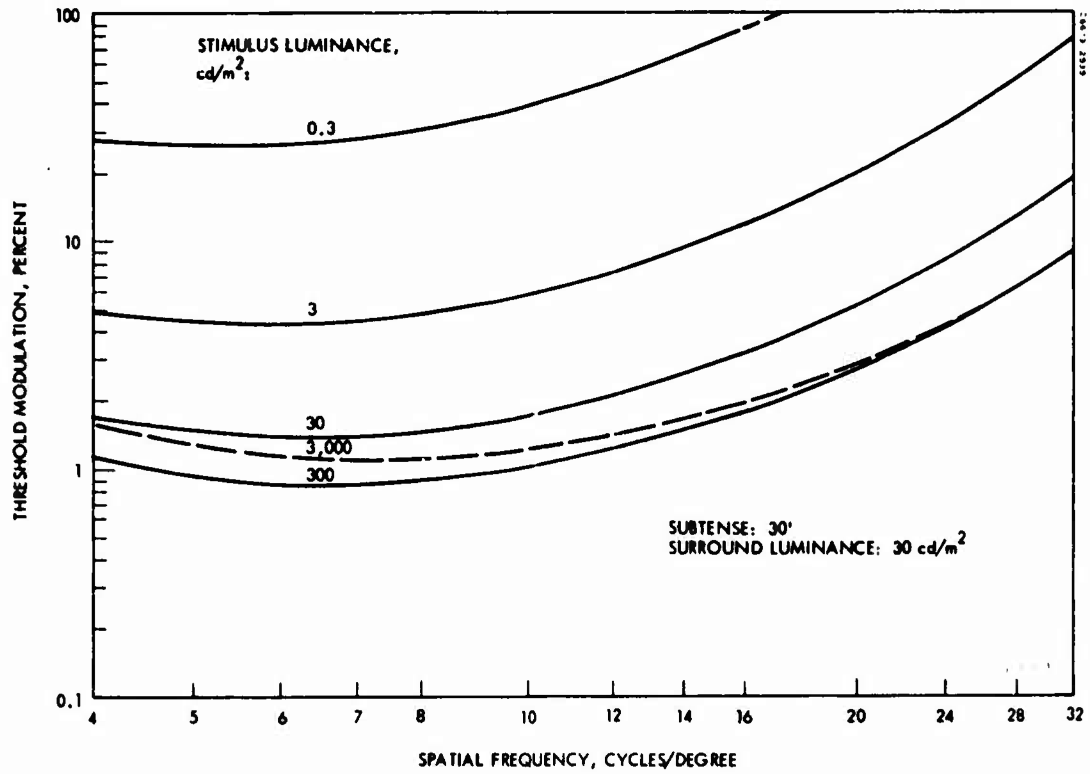


Figure 2-11. Modulation threshold as a function of spatial frequency at different stimulus luminances with surround luminance held constand. Visual subtense of stimulus is 30 arcminutes.

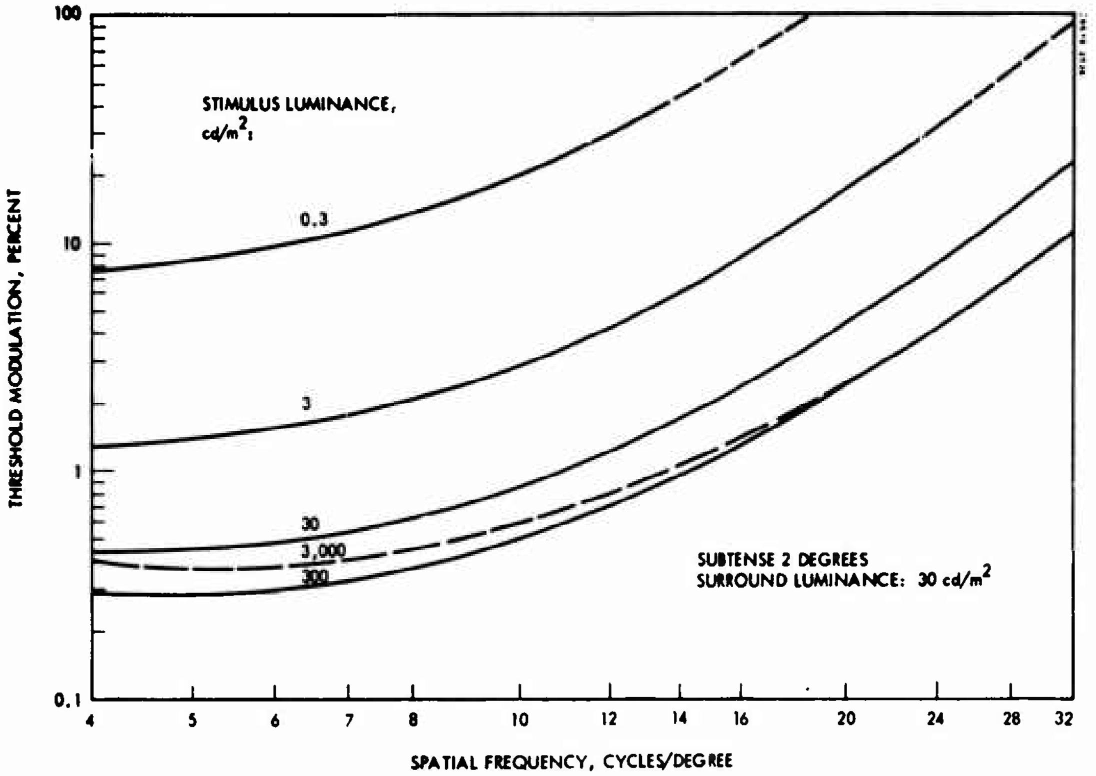


Figure 2-12. Modulation threshold as a function of spatial frequency at different stimulus luminances with surround luminance held constant. Visual subtense of stimulus is 2 degrees.

300 and 3000 fL stimulus luminances, by which the 3000 fL thresholds were elevated over those occurring at 300 fL luminance. This effect was verified with the raw experimental data in order to assure that it was not attributable to an artifact of the regression solution. The elevated thresholds are probably due to the glare of such a bright stimulus seen against a relatively dark background, and result from dispersion in the ocular media; they did not occur when stimulus and surround luminances were equal.

Surround Luminance

The effect of surround luminance on the contrast threshold with all other factors held constant is shown in Figure 2-13. This effect was not greatly dependent on spatial frequency, and evidences minimum threshold with a surround luminance of about 11 cd/m^2. Optimum stimulus/surround luminance ratios will be discussed subsequently.

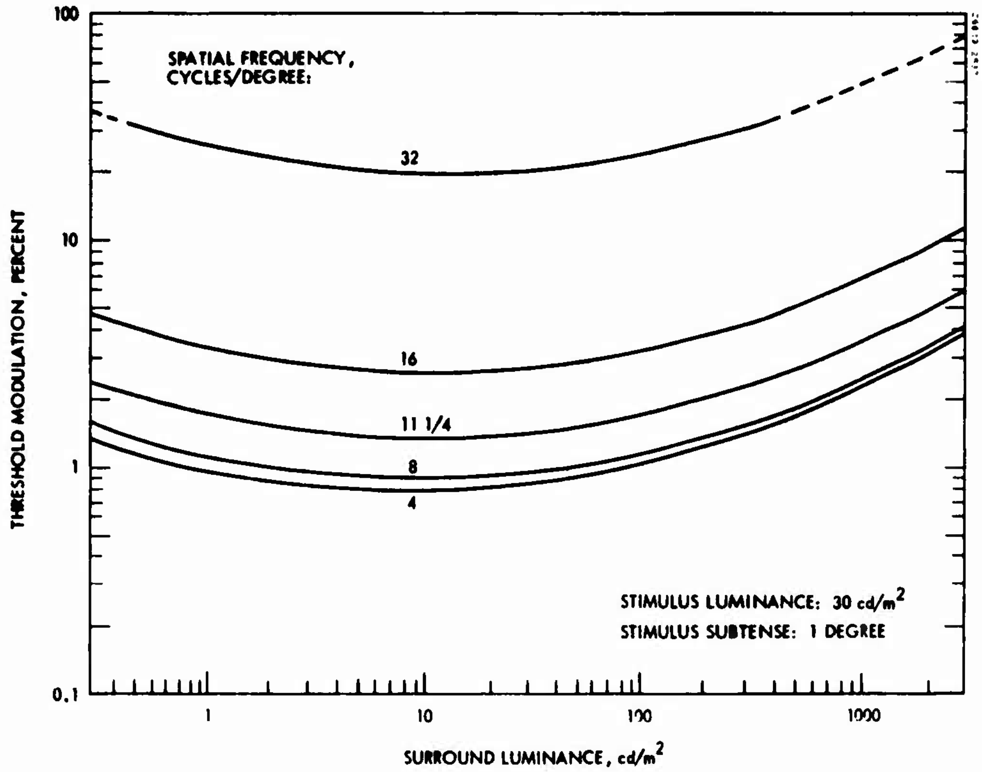


Figure 2-13. Modulation threshold as a function of surround luminance with stimulus luminance held constant. Spatial frequency is the parameter.

The major significance of surround luminance to the regression solution was as an interactive term with stimulus luminance. As an independent factor, surround luminance was not statistically significant; but its squared term was. Following are the f ratios of the five coefficients:

Stimulus Luminance:	14.86
(Stimulus Luminance)^2:	135.72
Surround Luminance:	2.62
(Surround Luminance)^2:	74.56
(Surround Luminance) x (Stimulus Luminance):	146.80.

Appendix B gives the method-of-adjustment thresholds calculated from the complete regression equation (Step 14) for the full range of stimulus and surround luminances, at spatial frequencies of 2, 4, 8, 16 and 32 cycles per degree and with stimulus sizes of 15 and 30 arcminutes and 1, 2 and 4 degrees subtense.

2.3 EXAMPLES OF DESIGN CRITERIA BASED ON PSYCHOPHYSICAL DATA

2.3.1 Preliminary Considerations

Table II-3 presented regression coefficients for the experimental variables and their first-order powers and interactions, as calculated at Step 5, Step 7, and Step 14 of the multiple regression program. Data discussed previously in the Results section were derived from the full regression equation (Step 14). For design purposes, however, maximum accuracy is seldom required, inasmuch as normal day-to-day variations both in equipment and in operator responses greatly exceed errors of approximation.

Step 5 was selected as the earliest computation to use, because it is the first which includes all variables either directly or as squared terms or interactions. Even so, the correlation coefficient of 0.9103 shows that more than 80 percent of the variability of the data have been accounted for at this stage. Step 7, with two more terms, accounts for more than 90 percent of the variability with a correlation coefficient of 0.9538. Table II-5 lists the coefficients of these two steps. Except where noted, subsequent calculations are based on this table.

TABLE II-5. THREE-DECIMAL APPROXIMATIONS OF STEPS 5 AND 7 OF REGRESSION EQUATION

Variable	Step 5	Step 7
A. Log Stimulus Luminance*	-0.646	-0.513
C. Log Stimulus Subtense	-0.414	-0.437
D. Log Spatial Frequency		-3.337
A^2.	0.136	0.153
B^2.	0.064	0.131
D^2.	0.740	2.310
AB.		-0.172
Constant Term	-2.123	-0.525

*Foot-Lamberts

A major advantage of the regression form of the experimental data is the ease with which the resulting equations can be transformed in order to derive secondary relationships. By holding certain variables constant while allowing others to change, it is possible to derive relationships which are useful in engineering tradeoffs. For instance, setting modulation equal to a constant permits solution of the basic equation in a manner that shows the different combinations of variables which combine to yield that value of modulation. If one of the variables (say, stimulus luminance) is limited to a given amount by equipment constraints, then requirements placed on the other variables by this fact become clear in the solution of the equation. This technique is utilized in subsequent sections to derive response contours for isofrequency, isoresolution, and isocontrast conditions. These will be explained more fully in the related discussions.

It was noted in the Results section that "Comfort" setting modulation thresholds were about 1.6 times the basic method-of-adjustment thresholds. It is reasonable to use this figure as a field factor by which to multiply threshold contrasts for use in the development of conservative design criteria. In what follows, equations are developed to both the threshold and the field-factor criterion; the latter are designated by the suffix "a" (e.g., Equation 2-4a).

Heretofore the international standard of candles per square meter (candela) has been employed as the unit of luminance, to facilitate comparison with other published research. In the United States, however, typical field instruments are calibrated in the older unit of foot-lamberts, and engineers are most familiar with that term. Graphs have consequently been presented in terms of both standards. Formulas are given in foot-lamberts.

2.3.2 Equal Stimulus and Surround Luminances

The most common application of MSF data will be for the case in which the average stimulus luminance and the surround luminance are the same. Because this condition was bracketed throughout the psychophysical study with comparatively few data points being taken at equivalent stimulus and surround luminances, it is necessary to calculate resultant modulation thresholds from the regression equation. This may be obtained from the full equation by entering the complete table of the preceding section; or a simpler form may be derived by letting A equal B in the approximate equation given above for Step 7. We then have:

$$M_t = 0.111A^2 - 0.513A - 0.437C + 2.310D^2 - 3.334D - 0.525 \quad (2\text{-}1)$$

$$M_t = 0.111A^2 - 0.513A - 0.437C + 2.310D^2 - 3.334D - 0.321 \quad (2\text{-}1a),$$

where

A = Log stimulus and surround luminance, foot-lamberts

C = Log stimulus subtense, degrees

D = Log spatial frequency, cycles per degree

M_t = Log modulation at threshold.

Example 1

Assume that the recognition of a certain target involves the perception of spatial frequencies of at least 16 cycles per degree with an average display luminance of 50 foot-lamberts. Distance and field of view require that the target be recognized by the time that it subtends 15 arcminutes on the display. Calculate the minimum modulation required on the display.

$$A = \log 50 = 1.699$$

$$C = \log (15' \times 1^{\circ}/60') = -0.602$$

$$D = \log 16 = 1.204.$$

Using Equation (1a) which incorporates the field factor,

$$M_t = 0.111(1.699)^2 - 0.513(1.699) - 0.437(-0.602) + 2.310(1.204)^2$$
$$- 3.334(1.204) - 0.321$$

$M_t = -1.275$

$m_t = 0.053.$ (Captial letters used for logarithms of variables; small letters for the variables.)

Example 2

The raster of a 5-inch CRT exhibits an effective line-to-space modulation of about 20 percent. At a luminance of 100 foot-lamberts and a viewing distance of 30 inches, how many lines are required to prevent the raster structure from being objectionable?

This display subtends a viewing angle of $2 \tan^{-1} (2.5/30) =$ 9.527 degrees. Although this is greater than the largest stimulus used in the foregoing study, for reasons given above it seems proper to extrapolate this particular variable over a range of two or three to one. Alternatively, one could adopt the approach of using the largest value of stimulus subtense (C) studied in the experiment whenever the actual display size exceeds this value. Both methods will be illustrated.

It should be recalled that the values of contrast calculated by the regression equation are those for which the stimulus is readily visible — not those which are liminally perceptible. Thus one should expect the solution to give an indication of when the raster will become salient or objectionable, rather than when it will just become detectable.

Solution No. 1: Actual Size

$$A = \log 100 = 2.000$$

$$C = \log 9.527 = 0.979$$

$$M_t = \log 0.200 = -0.699$$

Since visibility is not desired, Equation (2-1) will be used instead of Equation (2-1a). Rewriting Equation (2-1) and solving for D, we have

$$D = 0.722 + (-0.048A^2 + 0.222A + 0.189C + 0.433M_t + 0.748)^{1/2} \quad (2\text{-}2)$$

$$D = 1.661$$

$$d = 45.85 \text{ cycles/degree} = 437 \text{ lines}$$

Solution No. 2: Let Size = 4 Degrees

$$A = \log 100 = 2.000$$

$$C = \log 4.000 = 0.602$$

$$M_t = \log 0.200 = -0.699$$

Now

$$D = 1.673$$

$$d = 41.94 = 400 \text{ lines}$$

Thus the first approach is actually more conservative than the second; although, it involved the quesionable practice of extrapolating beyond the range of the experimental variable. The reason is to be found in the slope of the function with respect to the size variable, and in its fairly rectilinear form in this region. Furthermore, it will be recalled from the regression that was performed on existing literature and reported in the first section of this study that thresholds appear to decrease with increasing size up to about 15 degrees. This conclusion was formed from the examination of several disparate studies, which is also a tenuous foundation for design. All of these factors taken together, however, point in the same direction and strongly imply that, in this case, the extrapolation is justified. Solution No. 1 is therefore the preferred solution.

Graphs for Equal Stimulus and Surround

Because this condition is encountered so frequently, we have made the substitution of A = B performed in Equation 2-1 in the complete regression equation (Step 14) and solved it for a range of display luminances. These solutions are plotted in Figures 2-14 through 2-18 for each of the angular subtenses employed in the experiment.

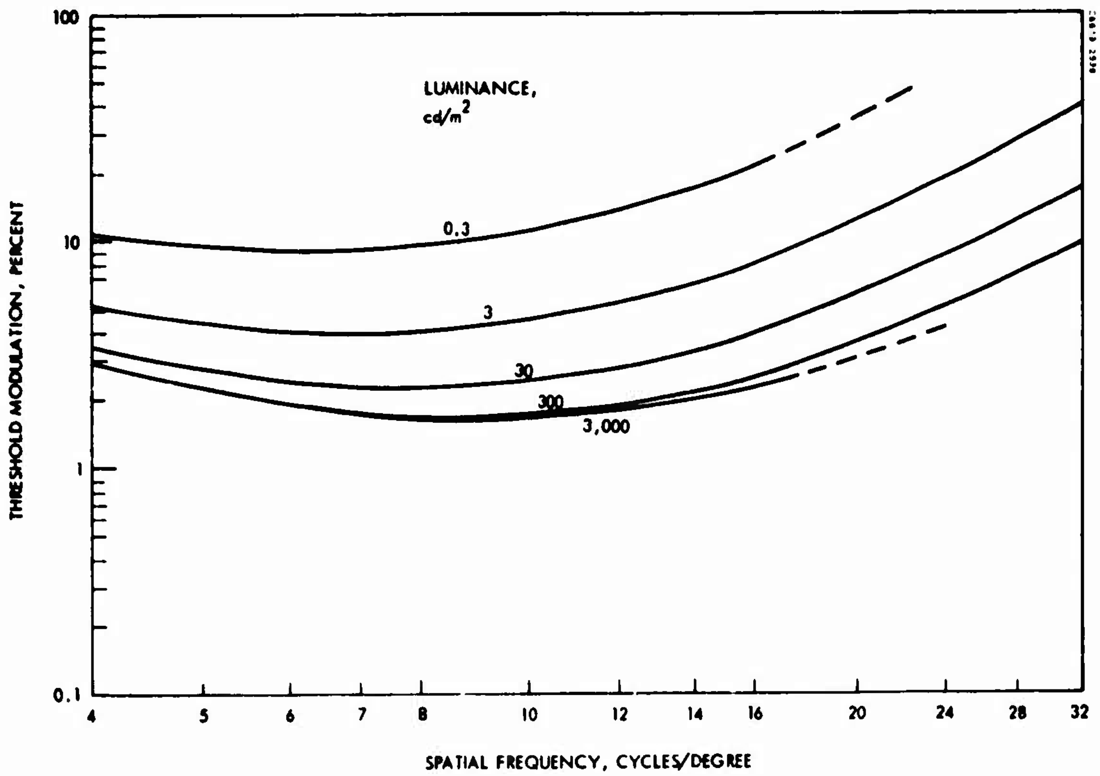


Figure 2-14. Modulation thresholds for equal stimulus and surround luminance at 15 arcminute subtense.

2.3.3 Isofrequency Response Contours

Determining modulation threshold as a function of luminance, with spatial frequency appearing as the parameter, permits easy tradeoff of contrast, dynamic range, gray shade range or modulation value against available display luminance.

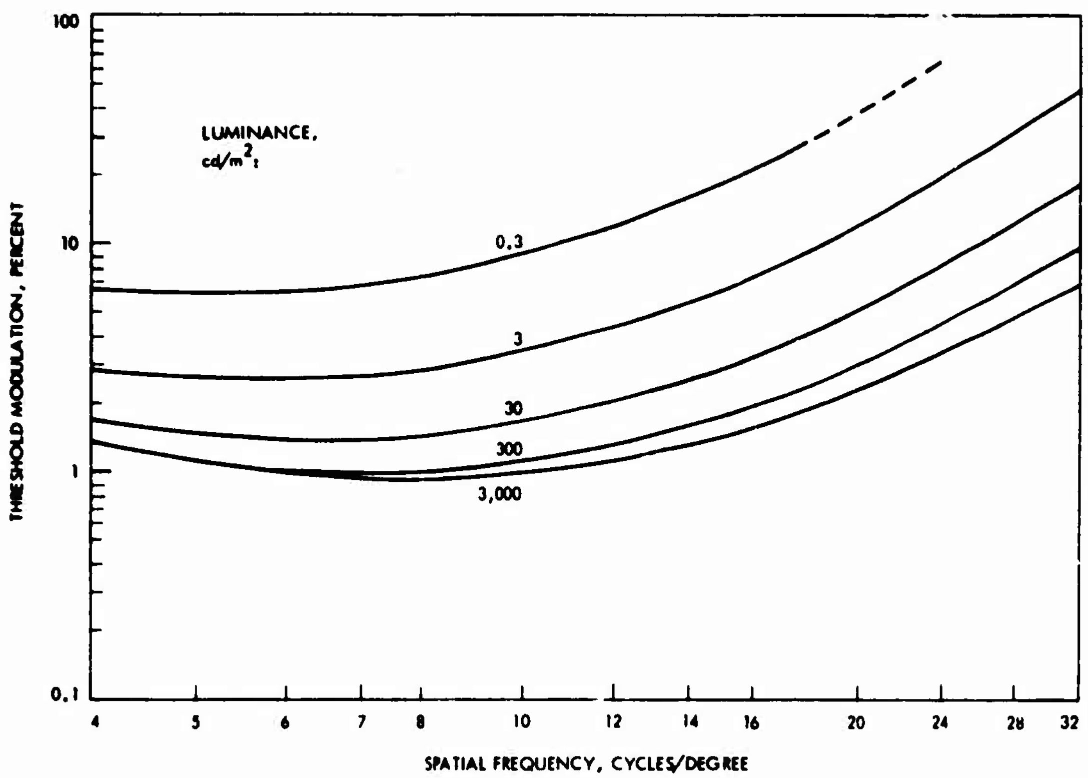


Figure 2-15. Modulation thresholds for equal stimulus and surround luminance at 30 arcminute subtense.

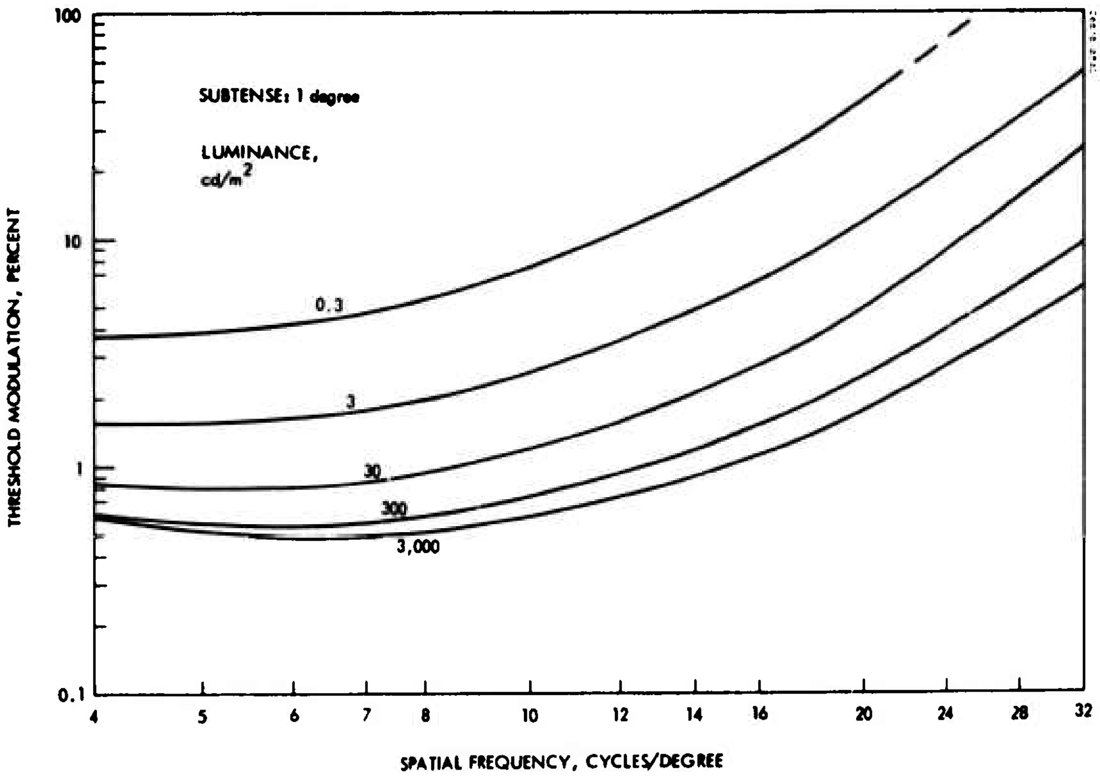


Figure 2-16. Modulation thresholds for equal stimulus and surround luminance at 1 degree subtense.

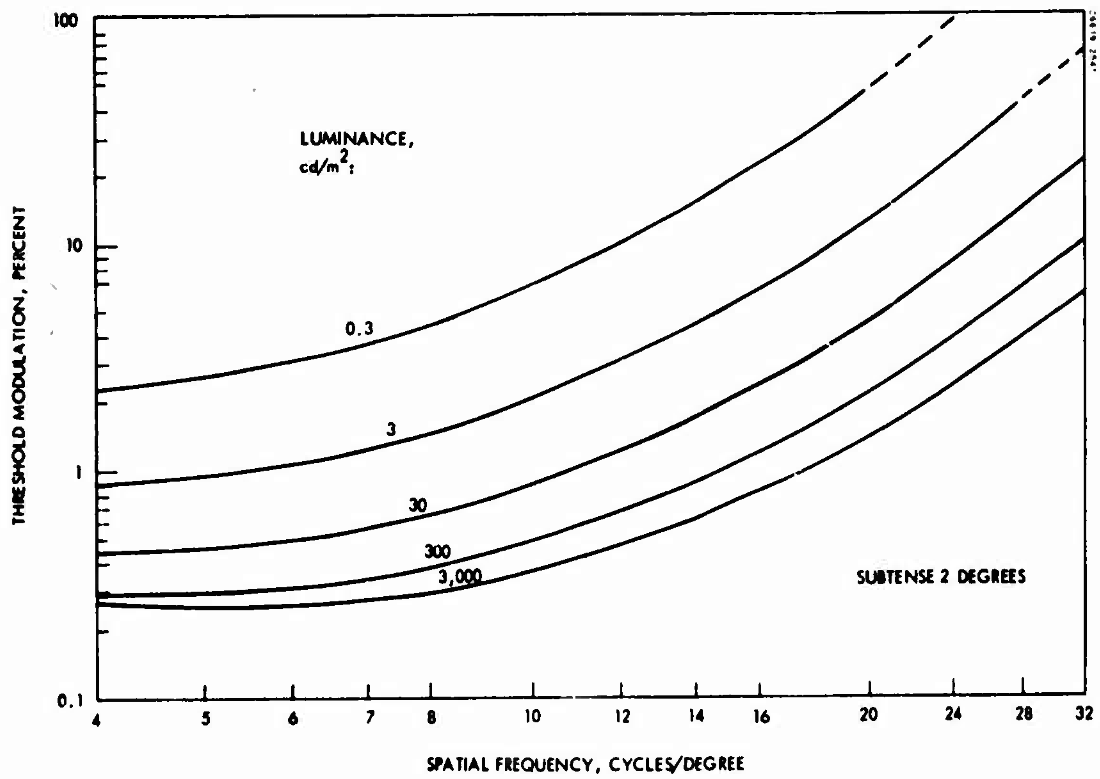


Figure 2-17. Modulation thresholds for equal stimulus and surround luminance at 2 degree subtense.

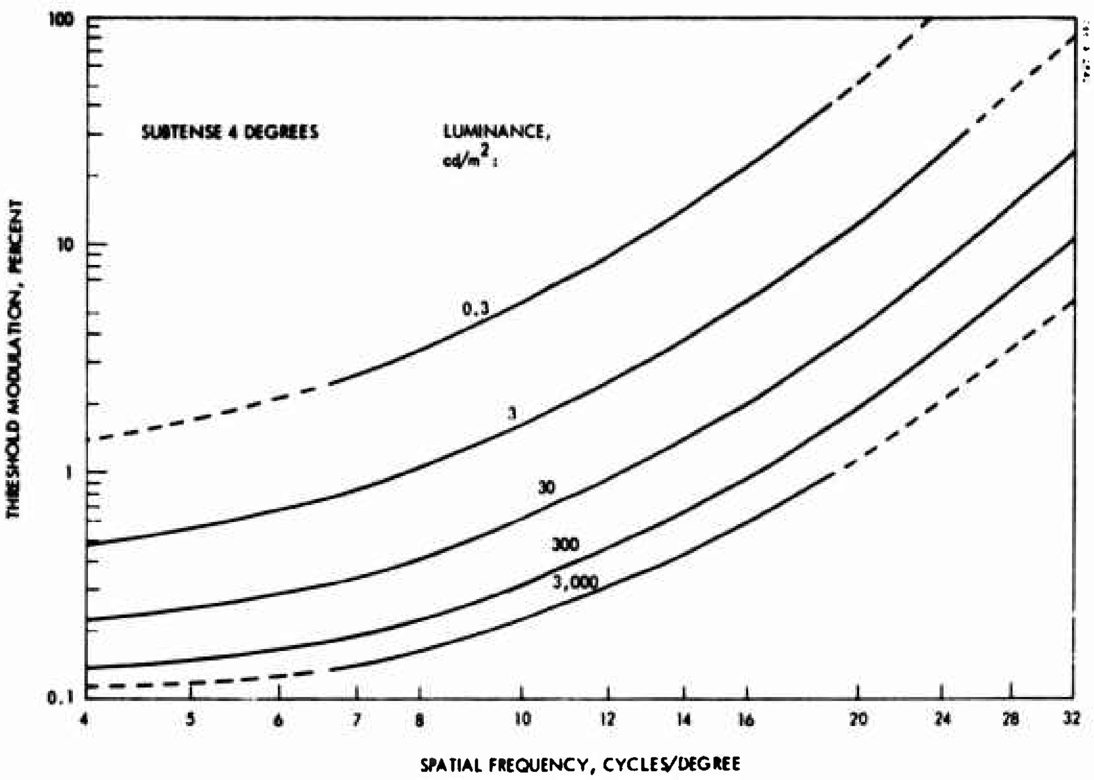


Figure 2-18. Modulation thresholds for equal stimulus and surround luminance at 4 degree subtense.

This utilizes the same set of data presented above but plotted in a different manner. Its solution utilizes Equation (2-1). Once the spatial frequency requirement for a given visual task has been determined, one may calculate corresponding values of modulation and luminance which fall along that isofrequency contour from Equation (2-1), or refer to the graphs in Figures 2-19 through 2-21. For displays subtending 4 degrees or more in which target subtense is not specified, the 4-degree graph should be used.

Example 3

A 5-inch display required to be viewed at 30 inches has a maximum dynamic range of ten to one. It is estimated that a typical target will exhibit a contrast of 10 percent of the full range against its background. Determine the minimum average display luminance, assuming the mission requires the visibility of spatial frequencies up to 32 cycles per degree.

The highest modulation which can be achieved within a total dynamic range of ten to one is $(10-1)/(10+1) = 0.818$. We therefore have

$$M_t = \log (0.818 \times 10\%) = -1.087$$

$$C = \log (2 \text{ arc tan } 2\text{-}1/2/30) = 0.979$$

$$D = \log 32 = 1.505.$$

Solving Equation (2-1) for A yields

$$A = 2.311 - (9.009M_t + 3.937C - 20.811D^2 + 30.036D + 10.070)^{1/2} \quad (2\text{-}3)$$

Incorporating the field factor of 1.6, we have

$$A = 2.311 - (9.009M_t + 3.937C - 20.811D^2 + 30.036D + 8.232)^{1/2} \quad (2\text{-}3a)$$

Making the above substitutions in Equation (2-3) results in

$$A = 0.8275$$

$$a = 6.7 \text{ foot-lamberts } (23 \text{ cd/m}^2).$$

Whereas Equation (2-3a) yields

$$A = 1.711$$

$$a = 51.4 \text{ foot-lamberts } (176 \text{ cd/m}^2).$$

A graphical solution (Figure 2-21) gives an estimate of 160 foot-lamberts for the minimum display luminance under these conditions. This is probably the greatest discrepancy we shall encounter, and calls for explanation.

The graphs of Figures 2-19 through 2-21 have been drawn from the full regression equation, which represents the best fit of the experimental

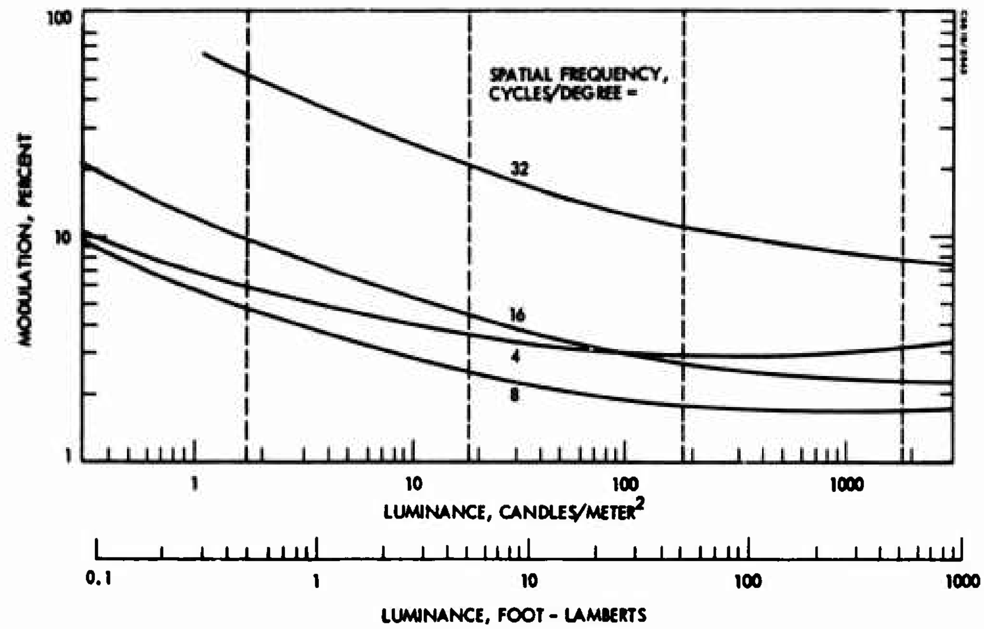


Figure 2-19. Isofrequency response contours for 15 arcminute subtense.

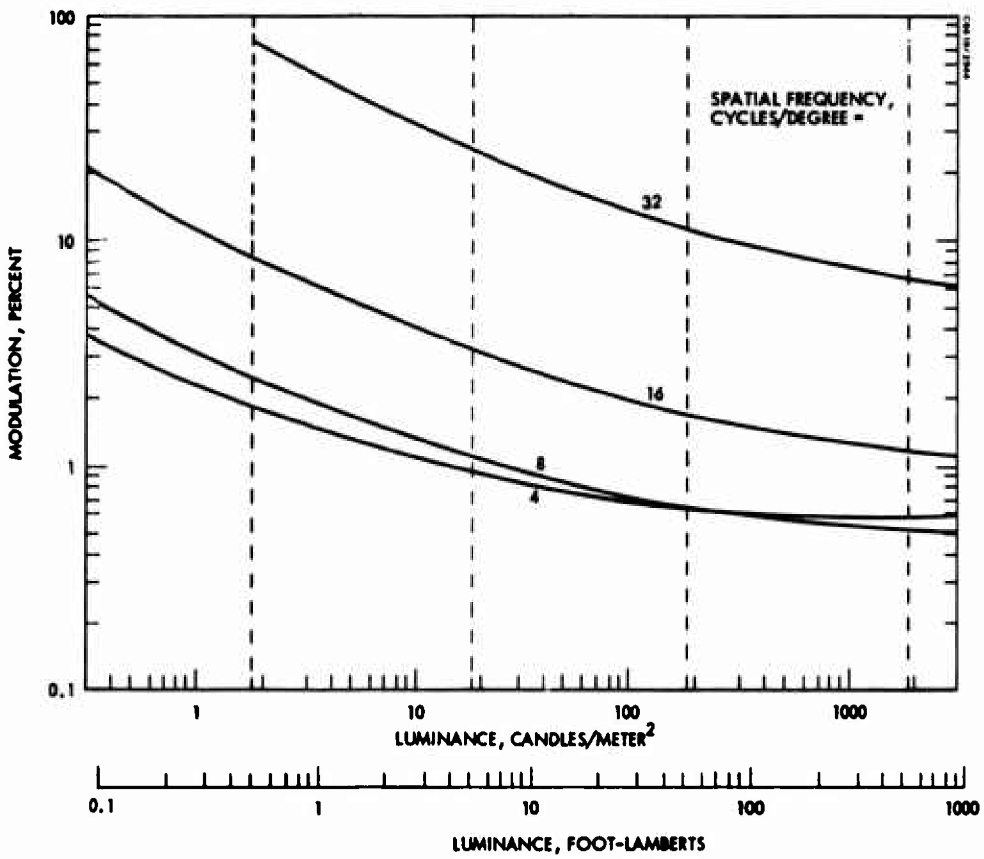


Figure 2-20. Isofrequency response contours for 1 degree subtense.

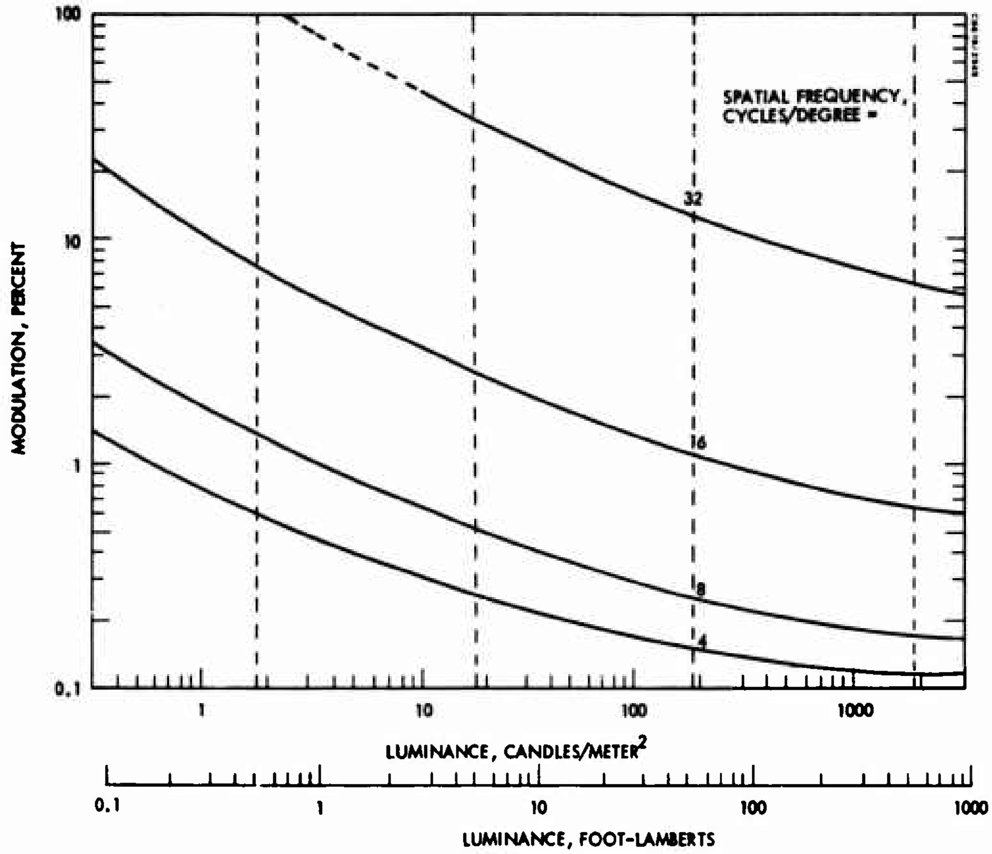


Figure 2-21. Isofrequency response contours for 4 degree subtense.

data. Not all of the coefficients of this complete equation are statistically significant, however. In particular, the coefficients for B, C^2, AC and BD were nonsignificant at $P < 0.10$, which implies that their effect in the regression equation cannot be attributed to other than chance variability of the experimental data. Indeed, the f-ratios for the latter three were less than one, indicating that they are strongly correlated with other, more significant coefficients. But their inclusion in the equation has an effect on the solution.

This effect will be greater, the greater the departure of a given data point from the center of the experimental volume. For the above example, we have deliberately chosen two values — those for spatial frequency and subtense — which are at or beyond the experimental range of values. Thus the present example represents a worst-case combination of two sources of error: extrapolation beyond the limits of the experiment, and operation in a region where error variance is known to be high.

In such cases, paradoxically enough, it is better not to use the entire regression equation. The full equation represents the best fit to the set of data points used in the experiment, including effects which cannot be ascribed to other than chance variation in subject response. One can make statements about this set of points using the complete equation; but one cannot make valid predictions about the experimental volume in general as long as these effects remain to bias the estimate. An unbiased predictive equation must be based on factors which are statistically significant.

All of the coefficients computed at Step 7 are statistically significant at $P < 0.01$, which was one of the considerations which entered into its selection as a basis for an approximate equation. Not only does it serve that purpose, however, but, as the preceding demonstrates, it actually provides a better basis for prediction than does the full regression equation. Hence, Equation (2-1) has greater predictive validity than the graphical solution derived from the complete regression equation.

2.3.4 Isoresolution Response Contours

The capacity for visual recognition of target images is commonly thought to be closely related to the resolution with which the image is presented to the observer. As pointed out previously, placing a resolution constraint on a target engenders a fixed reciprocal relationship between target subtense and spatial frequency. Inasmuch as Equation (2-1) encompasses both variables, it is possible to rewrite the equation so as to express the modulation threshold in terms of target size and resolution, rather than of target size and spatial frequency. Solution of this equation allows the determination of isoresolution response contours, by which contrast and resolution (that is, number of lines across the target) may be traded off.

It is also interesting to plot isocontrast contours against size and resolution, in order that earlier research aimed at relating image subtense to the number of TV lines may be evaluated from the standpoint of visibility. Both of these topics are considered in this section.

Equation (2-1) may be written in terms of size and resolution by making the following substitution:

$$f = \frac{n}{2c},$$

where

f = spatial frequency

n = resolution (number of lines)

c = visual subtense.

Taking the logarithms and substituting in Equation (2-1), we have

$$M_t = 0.111A^2 - 0.513A + 2.310C^2 + 4.288C + 2.310N^2 - 4.725N - 4.620NC + 0.688. \quad (2\text{-}4)$$

Also, from Equation (2-1a) with the field factor, we have

$$M_t = 0.111A^2 - 0.513A + 2.310C^2 + 4.288C + 2.310N^2 - 4.725N - 4.620NC + 0.892. \quad (2\text{-}4a)$$

Example 4

A certain target presents an intrinsic target-to-background modulation of 5 percent and is to be viewed under an average luminance of 100 foot-lamberts. Previous studies with a similar mission have shown that 12 lines must be resolved for recognition. In terms of visual angle, how large must the target be before it is recognized?

Equation (2-1) must be solved for target subtense, C:

$$C = N - 0.928 - (0.433M_t + 0.189N - 0.048A^2 + 0.222A + 0.564)^{1/2} \quad (2\text{-}5)$$

From Equation (2-4a) we also have

$$C = N - 0.928 - (0.433M_t + 0.189N - 0.048A^2 + 0.222A + 0.475)^{1/2} \quad (2\text{-}5a)$$

where

C = log visual subtense, degrees

M_t = log threshold modulation (-1.962)

N = log resolution, number of lines (1.079)

A = log average luminance, foot-lamberts (2.000).

In the present example, we have the values given above in parentheses. Solving Equation (2-5) for these values results in

$$C = -0.262$$

$$c = \log^{-1}(-0.262) = 0.547 \text{ degree} = 32.8'.$$

Solving Equation (2-5a) gives

$$C = -0.134$$

$$c = \log^{-1}(0.134) = 0.734 \text{ degree} = 44.0'.$$

<u>Example 5</u>

It is required that a certain target be detected by the time it subtends 20 arcminutes at the viewing position. The maximum dynamic range of the display is 20:1. Assuming detection requires 8-line definition, how bright must the display be in order to detect a target with an intrinsic target-to-background modulation of (a) 5 percent, (b) 3 percent, (c) 2 percent?

This calculation requires the solution of Equation (2-4) for the luminance variable, A:

$$A = 2.311 - [9.009M_t - 20.811(C^2 + N^2) - 38.631C + 42.568N + 41.622NC - 0.858]^{1/2}. \qquad (2\text{-}6)$$

And, with the field factor,

$$A = 2.311 - [9.009M_t - 20.811(C^2 + N^2) - 38.631C + 42.568N + 41.622NC - 2.696]^{1/2}. \qquad (2\text{-}6a)$$

Utilizing Equation (2-6a) for solution (a), we have

$$M_t = \log(19/21 \times 5\%) = -1.344$$

$$C = \log(20'/60') = -0.477$$

$$N = \log 8 = 0.903,$$

yielding

$$A = 2.311 - (2.301)^{1/2} = 0.794$$

$$a = \log^{-1} 0.794 = 6.23 \text{ foot-lamberts } (21.3 \text{ cd/m}^2).$$

For Solution (b), substituting $M_t = \log(19/21 \times 3 \text{ percent}) = -1.566$ results in

$$A = 2.311 - (0.429)^{1/2} = 1.656$$

$$a = \log^{-1} 1.656 = 45.3 \text{ foot-lamberts } (155 \text{ cd/m}^2).$$

Similarly, for Solution (c) $M_t = \log(19/21 \times 2 \text{ percent}) = -1.742$, and

$$A = 2.311 - (-1.285)^{1/2} = 2.311 - j1.134.$$

As an imaginary or complex solution has no physical meaning in this case, we conclude that a target of such low intrinsic (2 percent) modulation will not be detected at a 20-arcminute subtense. This can be verified by selecting the highest practical value of average display luminance (for this example, say 200 foot-lamberts) and solving Equation (2-5a) for target size:

$$M_t = -1.742$$

$$N = 0.903$$

$$A = \log 200 = 2.301$$

$$C = 0.903 - 0.928 - (0.148)^{1/2} = -0.410$$

$$c = \log^{-1} - 0.410 = 0.389 \text{ degrees} = 23.4 \text{ arcminutes.}$$

Inasmuch as a target of the given luminance and modulation would have to subtend 23 minutes of arc for detection, it follows that the 20-arcminute target stipulated in Example 5 (c) is indeed not detectable.

Graphs

Figures 2-22 and 2-23 show isoresolution response contours for the two luminance conditions of 0.9 foot-lamberts (3 cd/m^2) and 87 foot-lamberts

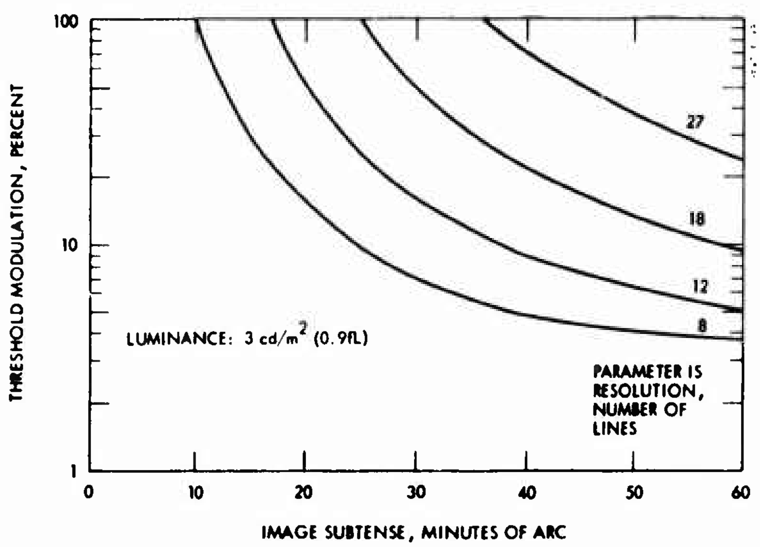


Figure 2-22. Isoresolution response contours for a dim (0.9 foot-lambert) target.

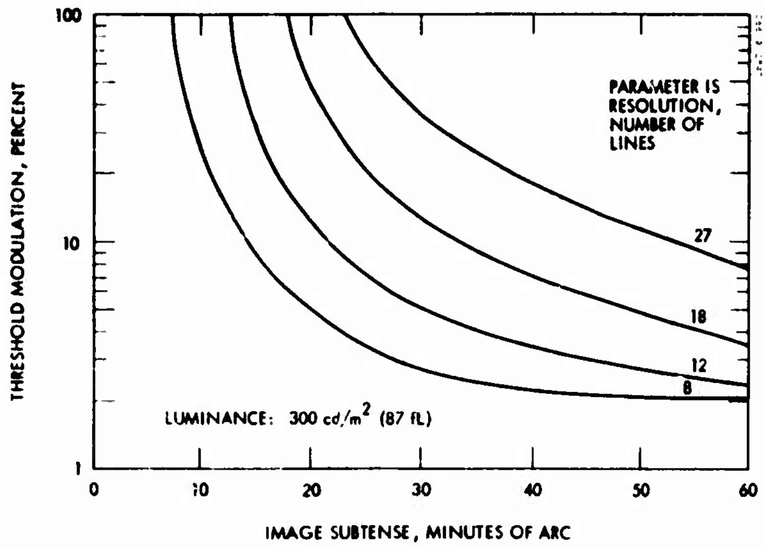


Figure 2-23. Isoresolution response contours for bright (87 foot-lambert) target.

(300 cd/m^2). As before, these are derived from the complete regression equation. The region below and to the left of each contour represents the set of images which are not visible for those combinations of conditions. The problems worked above may be checked on these graphs and found to yield approximately the same solutions.

2.3.5 Isomodulation Response Contours

It is of interest to plot the above data in slightly different form, in order that comparisons may be made between image size (subtense) and image definition (number of lines). Figure 2-24 shows this relationship. If a given modulation is required for detection, or if the display is capable of yielding only a given maximum modulation, then the region above and to the left of that isomodulation contour will be invisible.

2.3.6 Optima

The location of response optima with respect to individual factor levels may be calculated exactly by taking the partial derivative of the function with respect to the factor of interest, setting the resultant equation equal to zero, and solving.

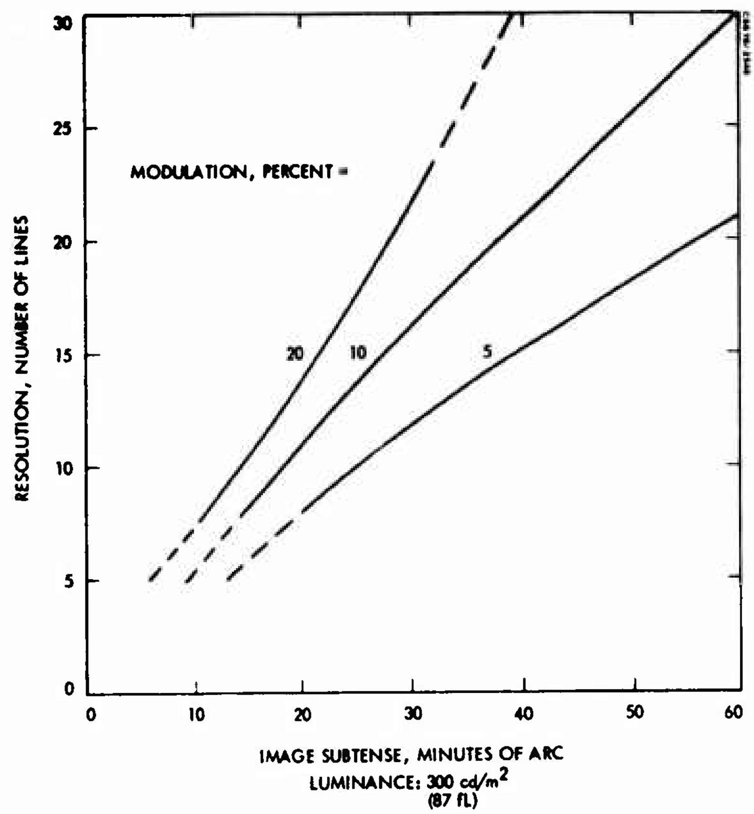


Figure 2-24. Isomodulation response contours. The region above and to the left of each contour is not detectable under the conditions noted.

The frequency-size interaction may be examined by taking the partial derivative with respect to size:

$$\frac{\partial M}{\partial C} = -3.36932 + 4.53128D + 1.24461C,$$

where

D = log stimulus size and

C = log spatial frequency.

(Luminances at median value of 30 cd/m^2)

Setting this equal to zero and solving yields an estimate of optimum stimulus frequency (that is, the spatial frequency which resulted in the lowest thresholds) as a function of stimulus size:

$$D = 0.74357 - 0.27467C$$

$$d = 5.54c - 0.275,$$

where

d = stimulus size and

c = spatial frequency.

Thus the spatial frequency yielding the lowest modulation threshold is estimated to be related to stimulus size in the following manner:

Subtense	Optimum Frequency
15 arcminutes	7.63 cy/deg
30 arcminutes	6.30 cy/deg
1 degree	5.21 cy/deg
2 degrees	4.31 cy/deg
4 degrees	3.56 cy/deg.

This relationship is graphically depicted in Figure 2-25.

Optimum luminance can be computed in a similar manner from the simultaneous solution of two equations:*

$$\frac{\partial M}{\partial A} = -0.48686 + 0.29874A - 0.19435B$$

$$\frac{\partial M}{\partial B} = 0.0834D - 0.19435A + 0.21184B,$$

*Taken from Step 8 of the regression solution.

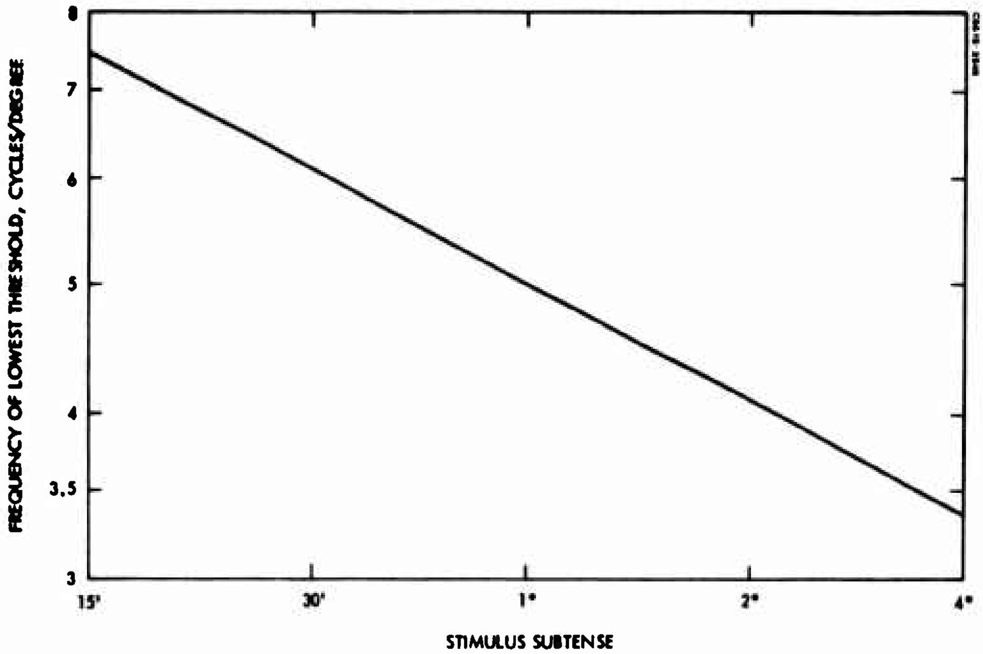


Figure 2-25. Spatial frequency corresponding to the lowest modulation threshold as a function of stimulus size (angular subtense).

where

A = log stimulus luminance and

B = log surround luminance.

In this case, the solution yields values of 8749 cd/m^2 and 1849 cd/m^2 for stimulus and surround respectively, which is outside the experimental volume. Inasmuch as the regression function was fitted only to values occurring within the experimental space, there is no assurance that these figures have meaning. We can conclude only that the range of luminances used in the study did not include simultaneous optima for stimulus and surround.

Using the second of the preceding equations, we can estimate the best surround luminance for a given stimulus luminance. Solved and transformed to linear variables, this results in:

$$b_{opt} = 0.404\ a^{0.917},$$

where

a = stimulus luminance, foot-lamberts

b = surround luminance, foot-lamberts.

A frequent visual task is the detection or recognition of stimulus subtending a small visual angle and containing finer internal structure. For example, a target subtending 15 arcminutes and requiring 8-line definition may have to be detected on a FLIR display. We have substituted the appropriate factor levels in the complete regression equation, with the following results:

Subtense: 15 arcminutes ($C = -0.505$)

$$\text{Frequency:} \quad f = \frac{2N - 1}{2\alpha} = 30 \text{ cy/deg } (D = 1.477),$$

where

N = number of lines and

α = subtense

$$\frac{\partial M}{\partial B} = 0.13092 + 0.21384B - 0.19435A = 0$$

$$B = 0.90886A - 0.61223$$

$$b = 0.244a^{0.909},$$

where

a = stimulus luminance, foot-lamberts and

b = surround luminance, foot-lamberts.

Stimulus Luminance	Surround Luminance
1	0.24
2	0.46
5	1.05
10	1.98
20	3.72
50	8.56
100	16.1
200	30.1
500	69.3
Luminances in foot-lamberts	

Thus, for optimum detectability/recognizability, a target of the above characteristics must be several times brighter than the surround. The two relationships described above are shown in Figures 2-26 and 2-27. Figure 2-26 depicts both the general case and the luminance ratios obtaining for the 8-line resolution condition; Figure 2-27 shows the general case again, using linear instead of logarithmic coordinates.

Overall luminance optima for display-background designs may also be implied from the general case. The largest stimulus used in the experiment subtended 4 degrees, whereas typical airborne displays subtend from 9 degrees (a 5-inch CRT viewed at 30 inches) to 25 degrees (a 14-inch CRT at the same distance). Although extrapolation beyond the experimental volume is generally a poor practice, in this case the straightness of the function and the fact that no other variables are involved at least partially justify extension to consideration of displays subtending 10 to 15 degrees.

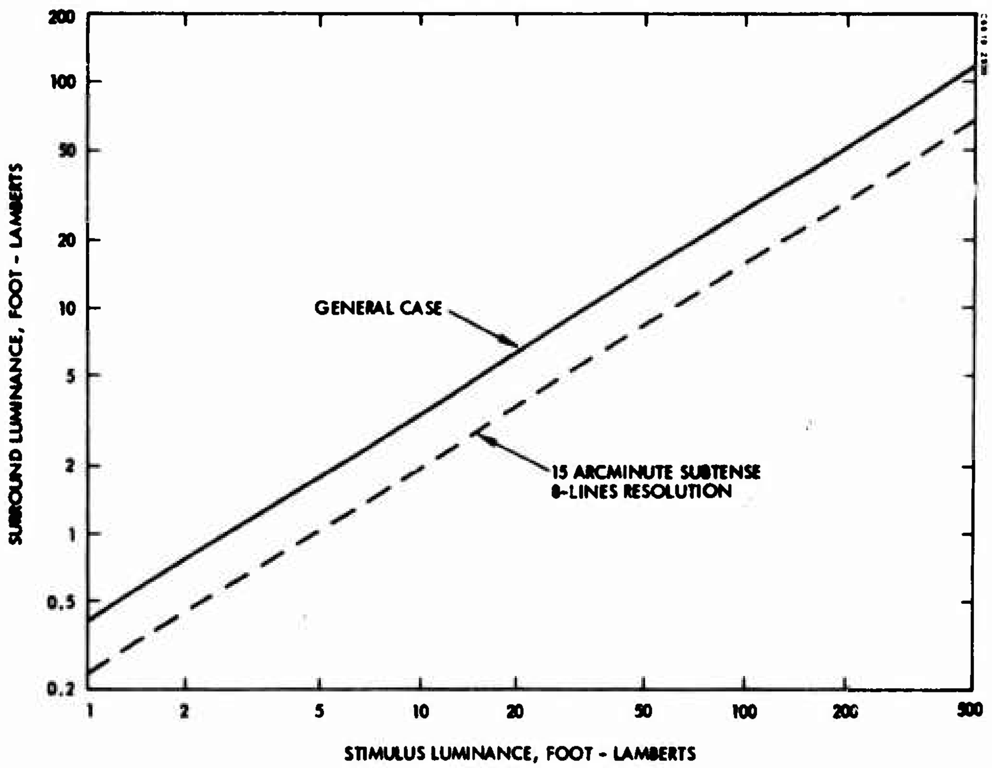


Figure 2-26. Best surround luminance related to stimulus luminance.

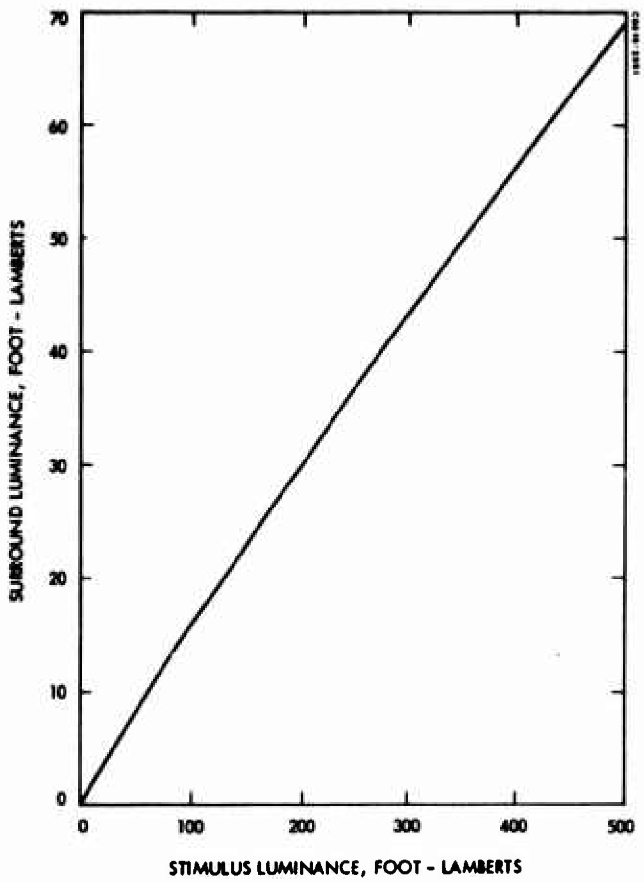


Figure 2-27. Best stimulus luminance as a function of surround luminance, assuming an 8-line definition criterion.

3.0 COGNITIVE DEMAND STUDIES

In the previous section, the response of the eye to intensity modulation as a function of a select set of variables was described. These data inform us only of the conditions under which elements of an image may be visually discriminated. To derive meaning or intelligence from an image the operator needs, of course, to make these discriminations, but in addition the target needs to be resolved both spatially and by modulation gradations. The granularity of the spatial and intensity information required for different kinds of recognition tasks has, in this program, been called the cognitive demand.

In quantized displays, pixels are picture elements — like the individual stitches in needlepoint or a sampler that, taken together, form a picture. How many stitches does it take to define a rose? a face? or an armoured personnel carrier? How fine should the stitches, the pixels, be? If the picture is monochromatic, how many values, shades of gray, are required? Tapestry artists have had to consider questions of this kind for centuries, taking full account of the viewing distance of the observers. Although the application is different, the same set of problems arise in the context of quantized displays used for target recognition. In the previous section, the conditions under which an individual pixel will be visible was determined. The experiments described below are a first step towards defining the cognitive demands of the observer; the number of pixels required to describe an object, the number of gray shades required, and the like.

Two pilot experiments were conducted to determine the sensitivity of operator performance in finding and recognizing targets to variations in a select set of display characteristics. Both studies dealt with quantized sensor information. One study used radar imagery and the other electro-optical imagery. The radar study was conducted as part of a different classified project, but the pertinent facts related to sensor display criteria are included in this report. These experiments are described below separately.

3.1 RADAR STUDY

Ground mapping radars are typically used by the operator to find stationary targets or landmarks whose coordinates are known and about which the crew will have been thoroughly briefed. The increasing planned use of digital scan conversion to map the radar video to the display raises the issue of the proper match between the capacity of the radar — its resolution, coverage, dynamic range, and modulation and the quantization intervals chosen for the scan converter. The effect of digital scan conversion is to spatially map the sensor data to the display by picture elements; pixels. The experimental display resolutions used in these studies are described by the number of pixels per display diameter or by the number of pixels per inch. The independent variables and fixed conditions chosen to the experiment are listed in Table III-1.

3.1.1 Imagery

The radar imagery was film records of high quality side-looking radar video. The same target area was mapped at two different radar ground resolutions which allowed the comparison of the effects of sensor resolution as distinct from display resolution. This imagery is classified and to keep this report unclassified, prints of the imagery or data concerning the radar resolution have been omitted.

3.1.2 Targets

Twelve radar targets were used in the experiment. The targets, target aimpoints, general target locations, and useful cues around the targets are given in Table III-2.

TABLE III-1. RADAR STUDY

INDEPENDENT VARIABLES	
SPATIAL QUANTIZATION:	247 PIXELS (34 per inch)
	514 PIXELS (71 per inch)
GREY SCALE QUANTIZATION:	4 GREY SHADES (2 bits)
	8 GREY SHADES (3 bits)
	16 GREY SHADES (4 bits)
FIXED CONDITIONS	
Display Size:	7-1/4 inches, square
Ground Coverage:	Constant (value classified)
Imagery:	Synthetic Array Radar
Radar Type:	Side Looking
Display Luminance:	10 fL
Ambient	1 fL
Display Dynamic Range:	50:1
INDEPENDENT VARIABLES	
Response Time	
Recognition Error	

TABLE III-2. TARGETS AND BRIEFING CUES

Target Number	Target Type	Target Airport	General Target Location	Useful Cues Around Target
1	3-way Road Junction	Center of Junction	Rural area	Inverted Y shape (λ) formed by roads leading to junction
2	Earthen Dam	Center of dam separating two bodies of water	Rural area	Shape of shore line of water
3	Freeway Overpass	Dead center on the overpass	Rural area	X-shape formed by the freeway and crossing road
4	Bridge	Center of bridge	Industrial-residential area	S-shape bend in river below target; horizontal orientation of road crossing river
5	Dirt Trail Junction	Center of Junction	Rural area	X shape formed by roads meeting at junction; contrast differences between one side of junction and the other
6	Corner of Field	Upper left corner of field	Rural area	Contrast difference between field and background irregular; shaped field to upper right of target
7	Stream Junction	Center of stream junction	Rural area	Contrast difference which splits the moor almost directly in half; runs through the steam junction
8	Bend in road	Center of bend in road	Rural area	L-shape of road
9	Junction of road and canal	Center of junction	Rural area	X-shape formed by crossing of road and canal; irregular shaped patch of trees to upper right of target
10	Power Plant	Center of power plant	Industrial-residential area	Shape of the body of water adjoining the power plant
11	Administration Building	Dead center on roof of building	Residential area	Freeway complex forms sideways Y around target area; target located near housing development
12	Building	Center of roof	Rural area	Backwards L-shaped road to left of target

3.1.3 Laboratory Equipment

The principal parts of the Hughes simulator used in this study are depicted in Figure 3-1. In the upper left are shown two sensor simulation devices — a television scanner (TVS) and a cathode ray tube (CRT) flying spot scanner (FSS). These units scan rear-illuminated photographic film imagery to produce video data simulating video from an electro-optical or radar sensor. For these studies the television scanner was used.

Analog video data from the scanner is displayed directly on the variable line and frame rate TV monitor located within the Operator's Console. The video may be digitized or analog. For these studies, the analog video was converted to digital format where gray levels were quantized to 2, 3, 4, 5, or 6 bits corresponding to 4, 8, 16, 32, and 64 gray shades. In addition, the brightness transfer function (BTF) may be varied from a linear function to one of 10 different non-linear relationships. For these studies, the BTF was visually selected to provide a pleasing picture and was subsequently measured.

A 14-inch television monitor was used as the video display. The raster on the display was adjusted to a width of 7-1/4 inches and a height of 7-1/4 inches.

When the oblique view characteristic of E-O sensors is simulated, closure on the target is provided with a servo driven 20:1 zoom lens on the Television Scanner (TVS).

3.1.4 Operators' Task

The task of the 12 Hughes engineer-subjects was to designate the aim-point of the radar targets with a small pointer. Prior to each trial, the operator was thoroughly briefed using vertical aerial photographs of approximately the same scale as the displayed radar test imagery. He was also provided with sketches of the probable radar returns and was told the direction at which the radar was illuminating the target area. The combination of radar ground resolution, display resolution, and grey scale quantization was also provided the observer just before each experimental trial. Considerable time was devoted to briefing the observer in order that he might develop a

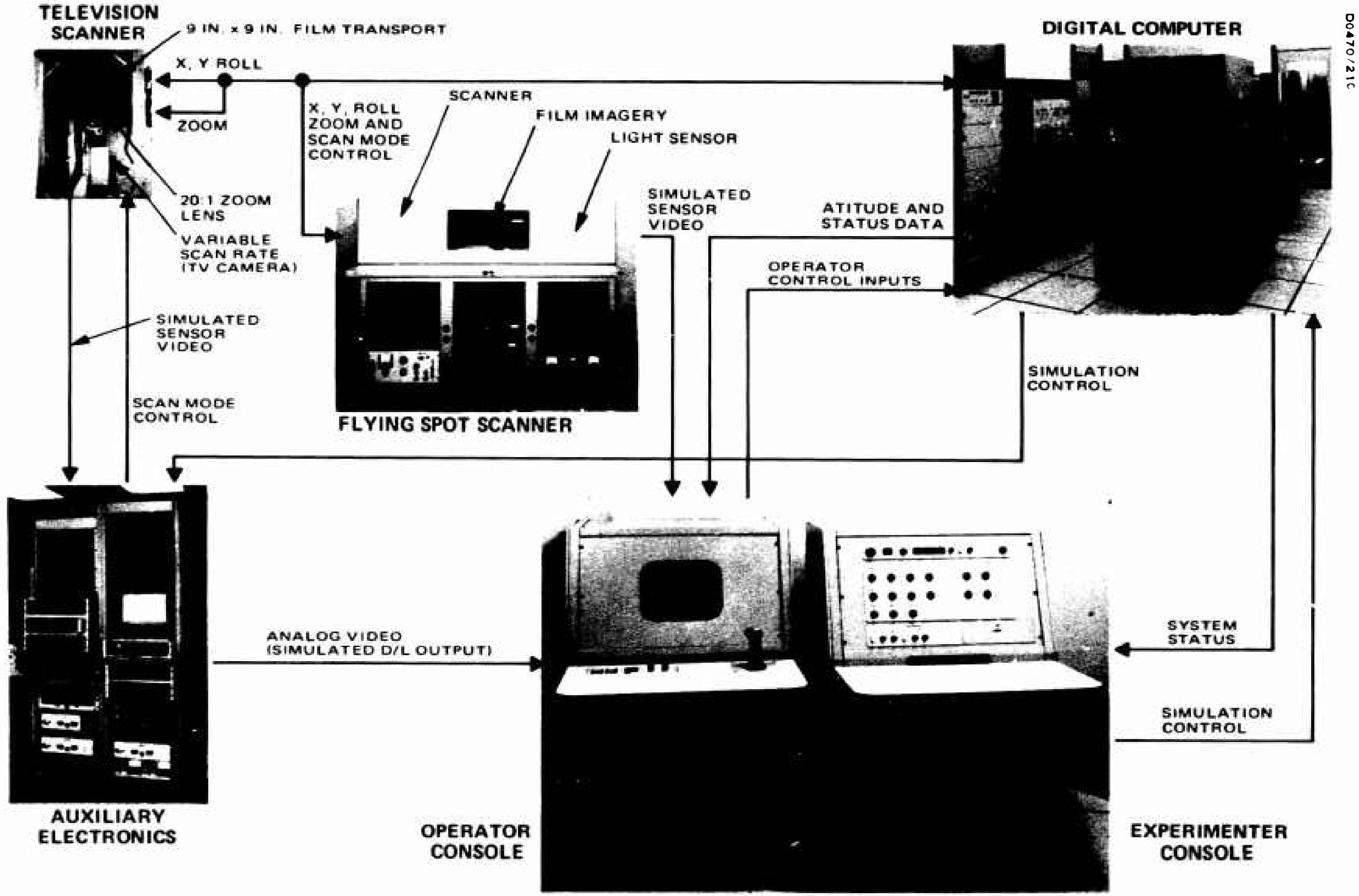


Figure 3-1. Hughes simulator.

mental picture of what to look for before a trial began. When he was ready, the stationary radar image was uncovered, and a stopwatch was started. When the observer found the desired target, he said "now", placed the crosshair over the target he had selected, and the trial was terminated. The experimenter recorded the elapsed time and whether or not the target aimpoint was correctly designated.

3.1.5 Results

Analyses of variance were computed using the proportion of correct target designations. The statistic Eta was calculated for all main effects and interactions to establish the percent of variance accounted for out of the total variance. A summary of the analysis is shown in Table III-3.

TABLE III-3. ANALYSIS OF VARIANCE SUMMARY: PROPORTION OF CORRECT TARGET RECOGNITIONS

Source of Variation	DF	SS	MS	ETA
1 Grey Scale Quantization	2	0.00815	0.00498	0.0283
2 Display Spatial Quantization	1	0.00241	0.00241	0.0084
3 Sensor Resolution	1	0.2324	0.23241	0.8063
1 x 2	2	0.02042	0.01921	0.0708
1 x 3	2	0.01482	0.00741	0.0514
2 x 3	1	0.00001	0.00001	0.00003
Residual 1 x 2 x 3	1	0.01002	0.01002	0.0348
Totals	11	0.28822		

Gray Shade Quantization

The main effect of gray shade rendition is shown in Figure 3-2. Cumulative percent probability of correct detection is plotted as a function of time. As can be seen from the graph, there was little performance difference between the 3- (8 gray levels) and 4-bit (16 gray levels) conditions.

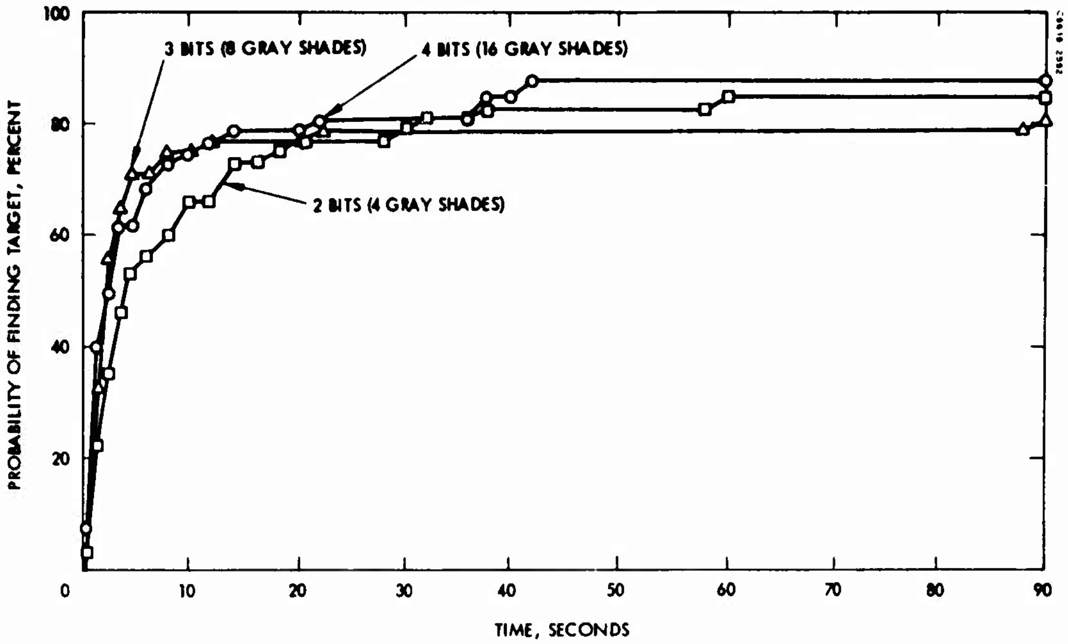


Figure 3-2. Probability of finding target as a function of time and gray scale quantization.

The 2-bit condition (4 gray levels) was inferior to the 3- and 4-bit conditions in the number of correct recognition responses made during the first few seconds. In terms of final performance (probability of correct target recognition), there was little difference between the 2-, 3-, and 4-bit conditions. The analysis of variance, Table III-3, indicates that the main effect of grey shade rendition failed to attain statistical significance.

Spatial Quantization

The main effect of spatial quantization can be seen in Figure 3-3. As can be seen from the graph there was a slight indication that the 71 pixel quantization fostered higher percentages of correct target recognition between 8 and 20 seconds. Terminal performance, however, appeared almost identical for the two conditions. Analysis of variance of the main effect indicates that this variable failed to attain statistical significance.

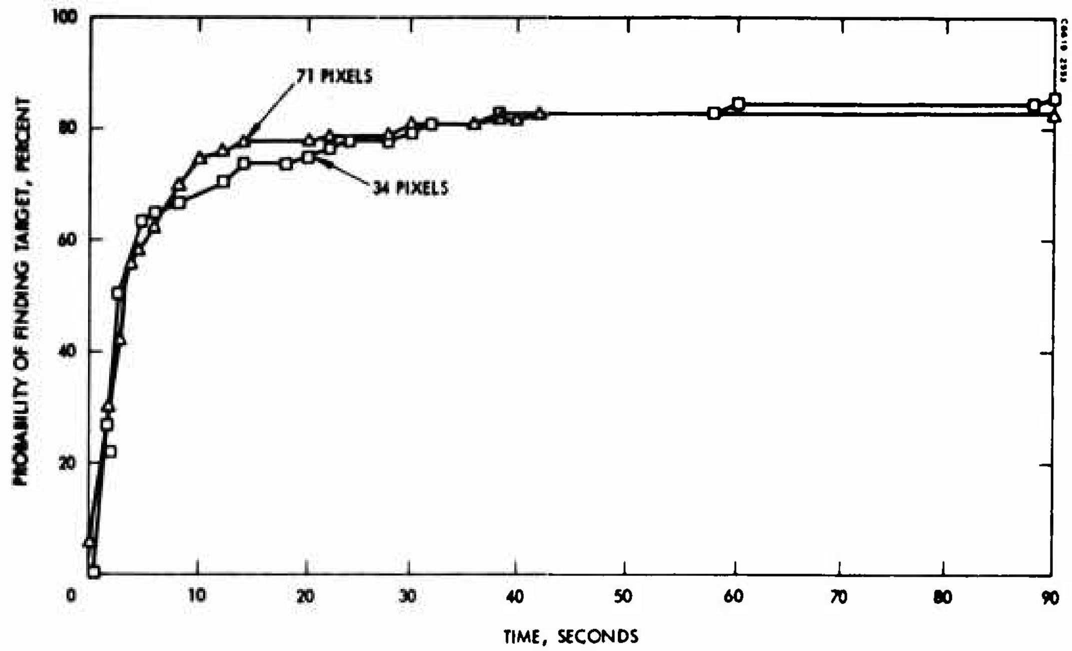


Figure 3-3. Probability of finding target as a function of time and display sp atial quantization.

Sensor Resolution

The main effect of sensor resolution can be seen in Figure 3-4. As can be seen from the graph, probability of correct detection under the high sensor resolution condition reached 80 percent after the first five seconds of the trials while the corresponding percentage for the low resolution was only 43 percent. The high sensor resolution retained its superiority over the low resolution through the duration of the trials with terminal performance reaching 98 percent for the high sensor resolution and 70 percent for the low resolution to be statistically significant at the 0.05 level. Calculation of the statistic Eta showed that the effect of sensor resolution accounted for 80 percent of the total experimental variance.

Interactions

None of the interaction was statistically significant. Plots of the results of the combination of high and low resolution radar with each of the display quantization levels are shown in Figure 3-5.

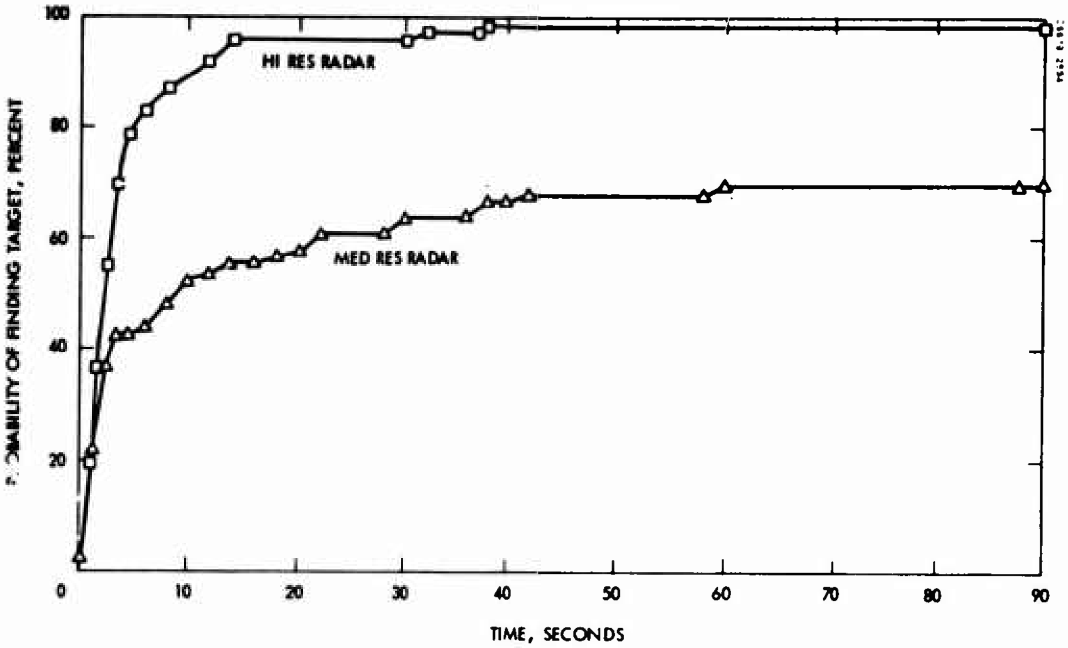


Figure 3-4. Probability of finding target as a function of time and radar resolution.

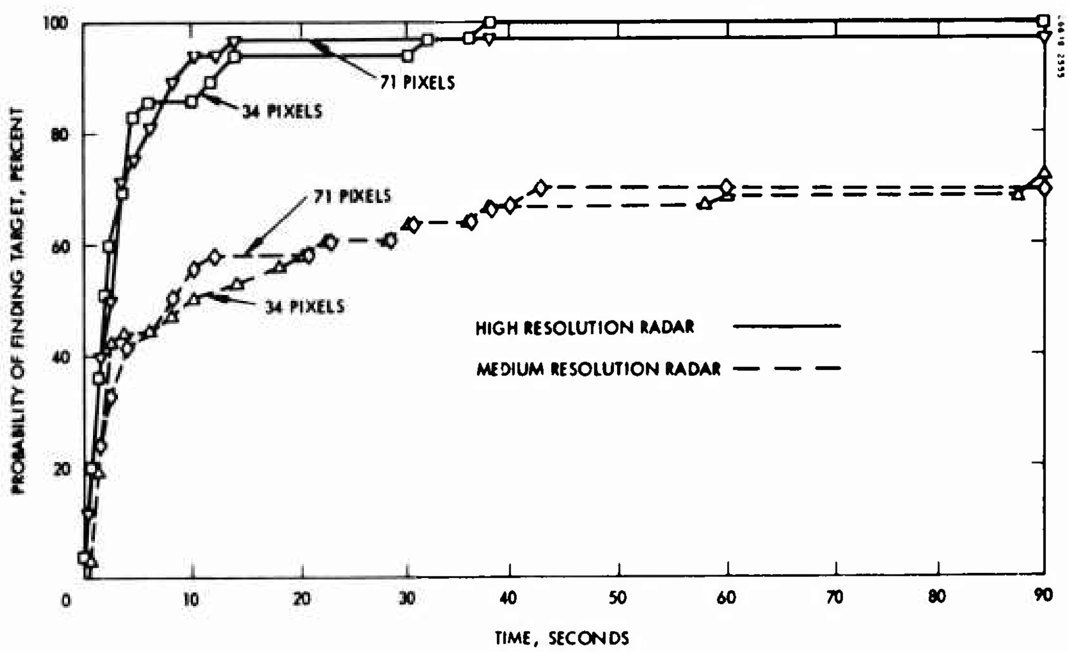


Figure 3-5. Probability of finding target as a function of time and spatial quantization, and radar resolution.

3.2 ELECTRO-OPTICAL STUDY

Unlike radar, electro-optical sensors may be used to recognize or identify fleeting and non-stationary small tactical targets. For the operator, this is a completely different task than finding a ground target on a radar display and depends not so much on the gestalt of the contextual information as on his ability to extract a shape signature from the displayed image. This, in turn, may require the discrimination of small modulations within the target. The recognition task, therefore, is expected to be much more sensitive to variations in quantized video. This study was undertaken to study these effects. The experimental variables are listed in Table III-4.

TABLE III-4. ELECTRO-OPTICAL STUDY

INDEPENDENT VARIABLES	
SPATIAL QUANTIZATION:	34 PIXELS per inch
	71 PIXELS per inch
GREY SCALE QUANTIZATION:	8 Grey Shades (3 bits)
	16 Grey Shades (4 bits)
	32 Grey Shades (5 bits)
FIXED CONDITIONS	
Display Size:	7-1/4 inches, square
Luminance:	10 fL
Ambient:	10 fL
Brightness Transfer Function:	Visually optimized for each image
Imagery:	Oblique Aerial Photographs
Subjects:	12 Hughes Engineers
INDEPENDENT VARIABLES	
Target size at recognition	
Definition at recognition	

3.2.1 Targets

All targets were vehicles. Six experimental, three dummy, and four training targets were chosen. The targets were: jeep, helicopter, 2-1/2-ton truck, tractor, tracked howitzer, and an armoured personnel carrier. See Figure 3-6.

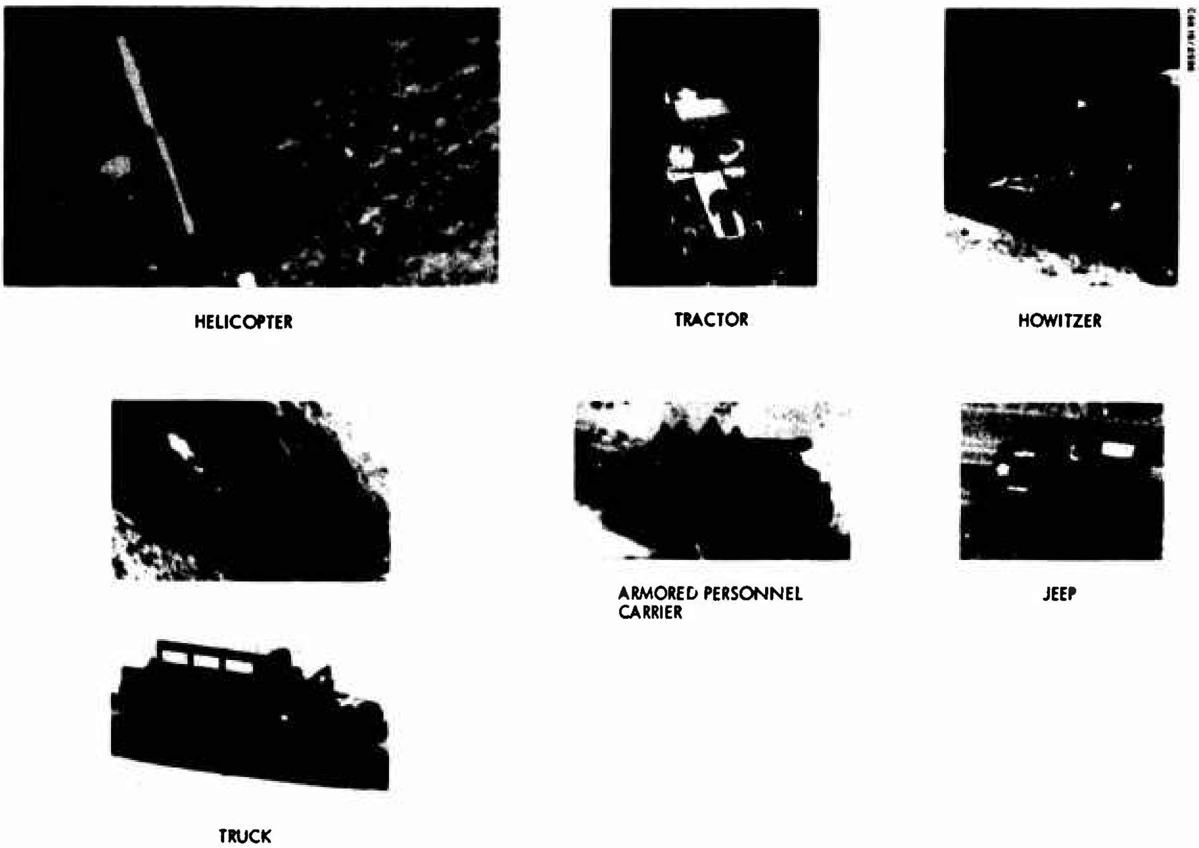


Figure 3-6. Targets used in experiment.

3.2.2 Imagery

The images from which the targets were selected were taken from low altitude oblique aerial photography. The originals were copied, cropped, and prepared for mounting in the equipment. Examples of one target in the various experimental conditions are illustrated in Figures 3-7 through 3-12.

Figure 3-7. Tractor: 34 pixels, 8 gray shades (3 bits).

Figure 3-8. Tractor: 34 pixels, 16 gray shades (4 bits).

Figure 3-9. Tractor; 34 pixels, 32 gray shades (5 bits).

Figure 3-10. Tractor: 71 pixels, 8 gray shades (3 bits).

Figure 3-11. Tractor: 71 pixels, 16 gray shades (4 bits).

Figure 3-12. Tractor: 71 pixels, 32 gray shades (5 bits).

3.2.3 Equipment

The equipment was identical to that used for the radar study except that a provision for observer controlled manual zoom was used.

3.2.4 Operators' Task

The task of the 12 Hughes engineer-subjects was to correctly name the target at the smallest size (furthest range) possible. Prior to the experimental trials, the observer was shown photographs of the six possible targets. These photographs were pasted on a board and were available for his inspection all the time. The object of the experiment was explained to the observer and four training trials were conducted to familiarize him with his task. In each trial, the subject started with the image at its smallest magnification. The target he had to identify was circled, and although the target could be seen at the smallest magnification, it could only be seen as a speck or small blob. By turning a potentiometer, the observer gradually increased the size of the image. His task was to increase the image size until he was reasonable certain about what the target was. Each time the observer made a response, it was recorded, and the size of the image was measured. The observer continued magnifying the image and correcting his original response if necessary until he reached the maximum magnification. The point at which the first correct response was made provided the basic data for the results.

3.2.5 Results

The size of the target at correct recognition was the primary dependent variable. For each trial, the longest dimension of the target at correct recognition was recorded. In addition the number of pixels across the target was calculated for each trial. Means and standard deviations for size and for pixels per target (definition) were calculated for each condition.

The results are illustrated in Figure 3-13 and tabulated in Table III-5. Grey scale quantization yielded poor performance for 3 bits (8 shades) but there was very little difference between 4 and 5 bits. This was true overall and within each of the spatial quantization levels. The level of spatial quantization affected operator performance markedly. Averaged across grey scale quantizations, the targets were recognized at 0.44 inch for the 71 pixel display and at 0.63 inch for the 34 pixel display. On the other hand, fewer pixels were required for recognition at the coarse spatial quantization than at the fine quantization; about 21 pixels for coarse to 31 for fine. This general relationship holds across grey scale quantization levels. Analyses of variance were calculated for both target size and definition (number of pixels per target). Eta's were also calculated for each variable. Eta provides an estimate of the percent of variance accounted for by each variable. The results of these analyses are shown in Tables III-6 and III-7.

These data may be converted to relative performance scores by normalizing to percentages. Using the size criterion, the best performance was obtained with 71 pixels and 32 grey shades. If this performance is called 100 percent, the relative performance of the other conditions is as

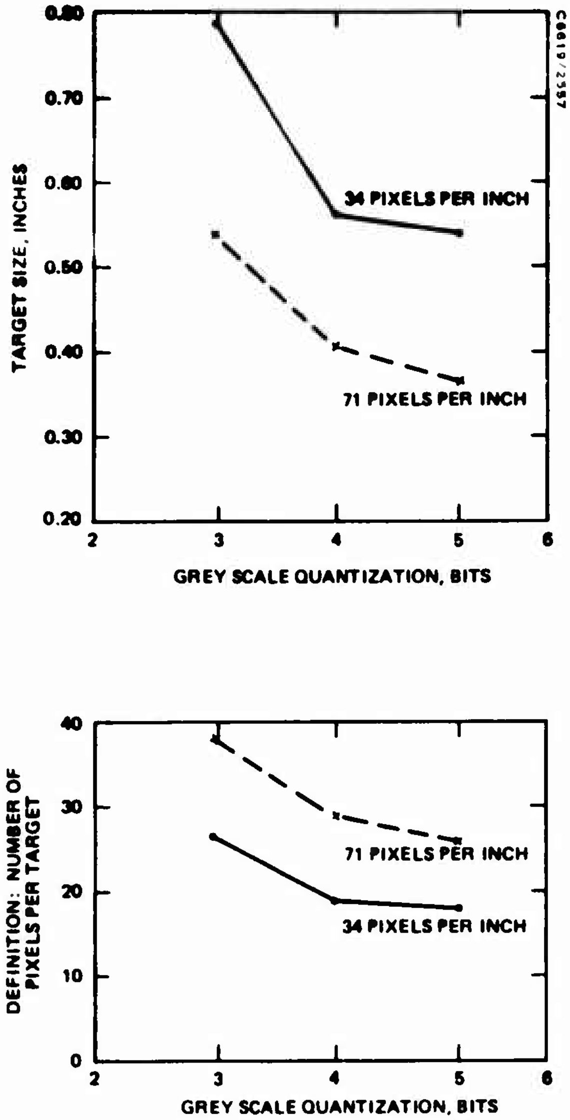


Figure 3-13. Size and defininition required for target recognition in the E-O study.

TABLE III-5. SPATIAL QUANTIZATION

Grey Scale Quantization	34 Pixels per Inch				71 Pixels per Inch							
	Target Size, inches		Pixels Per Target		Target Size, inches		Pixels Per Target		Target Size, inches		Pixels Per Target	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
3 bits (8 shades)	0.78	0.33	27	11	0.54	0.24	38	17	0.66	0.32	32	16
4 bits (16 shades)	0.56	0.27	19	9	0.41	0.11	29	8	0.48	0.22	24	10
5 bits (32 shades)	0.54	0.27	18	9	0.37	0.16	26	11	0.46	0.24	22	11
	0.63	0.31	21	11	0.44	0.19	31	14				

TABLE III-6. ANALYSIS OF VARIANCE SUMMARY: TARGET SIZE AT RECOGNITION

Source of Variation	DF	SS	MS	F	P	ETA
1 Spatial Quantization	1	0.6463	0.6463	18.42	0.001	11.69
2 Grey Shade Quantization	2	0.5985	0.2992	8.53	0.001	10.83
3 Targets	5	1.2009	0.2401	6.84	0.001	21.72
1 x 2	2	0.0295	0.0147	0.42		0.53
1 x 3	5	0.7811	0.1562	4.45	0.01	14.13
2 x 3	10	0.5030	0.0503	1.43		9.10
1 x 2 x 3	10	0.5050	0.0505	1.44		9.14
Replications	36	1.2633	0.0350			22.85
Totals	71	5.5281				

TABLE III-7. ANALYSIS OF VARIANCE SUMMARY: DEFINITION AT RECOGNITION

Source of Variation	DF	SS	MS	F	P	ETA
1 Spatial Quantization	1	1708.8	1708.8	23.81	0.001	13.59
2 Grey Shade Quantization	2	1413.2	706.6	9.85	0.001	11.24
3 Targets	5	2355.5	471.1	6.56	0.001	18.73
1 x 2	2	39.6	19.8	0.28		0.31
1 x 3	5	1342.2	268.4	3.74	0.01	10.67
2 x 3	10	1563.9	156.3	2.18	0.05	12.44
1 x 2 x 3	10	1568.8	156.8	2.19	0.05	12.47
Replications	36	2583.8	71.7			20.55
Totals	71	12576.[illegible]				

shown in Table III-8. Using the definition criterion, the best performance was obtained with 34 pixels and 32 grey shades. If this performance is called 100 percent, the relative performance of the other conditions is as shown in Table III-9.

TABLE III-8. RELATIVE PERFORMANCE USING SIZE CRITERION

Intensity Quantization	Spatial Quantization	
	34 Pixels Per Inch	71 Pixels Per Inch
3 bits (8 shades)	47%	68%
4 bits (16 shades)	66%	90%
5 bits (32 shades)	68%	100%

TABLE III-9. RELATIVE PERFORMANCE USING DEFINITION CRITERION

Intensity Quantization	Spatial Quantization	
	34 Pixels Per Inch	71 Pixels Per Inch
3 bits (8 shades)	67%	47%
4 bits (16 shades)	95%	62%
5 bits (32 shades)	100%	69%

3.3 DISCUSSION

The results of these two experiments, taken together, demonstrate the dependence of display design criteria on the task of the operator. The results from the radar study indicate that when the operator is thoroughly briefed, is looking for a target whose coordinates are known, and uses landmarks and contextual cues to find the target, the resolution and grey scale rendition of the display can vary over a wide range without having a major effect on radar target recognition performance. The critical variable is, of course, the characteristics of the sensor; the high resolution radar "sees" a different world than the medium resolution radar and the fact that those different worlds may be mapped to the display at different display resolutions makes little difference. A small difference occurs when the grey scale quantization falls below 3 bits.

Exactly the contrary is the case when the operator must recognize a target by its silhouette and small modulation differences within the target. Recognition performance of small electro-optical sensor targets as a function of the number of quantized grey levels takes a sharp dip when the grey levels fall below 16 (4 bits). The loss in performance as a function of grey levels is portrayed in Figure 3-14.

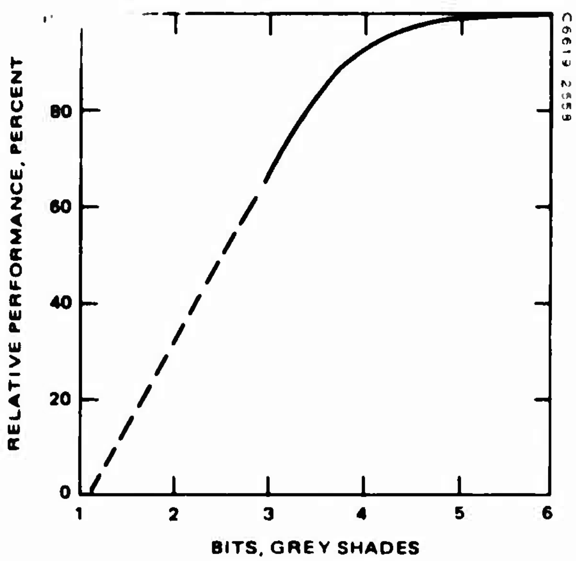


Figure 3-14. Relative recognition performance as a function of gray scale quantization.

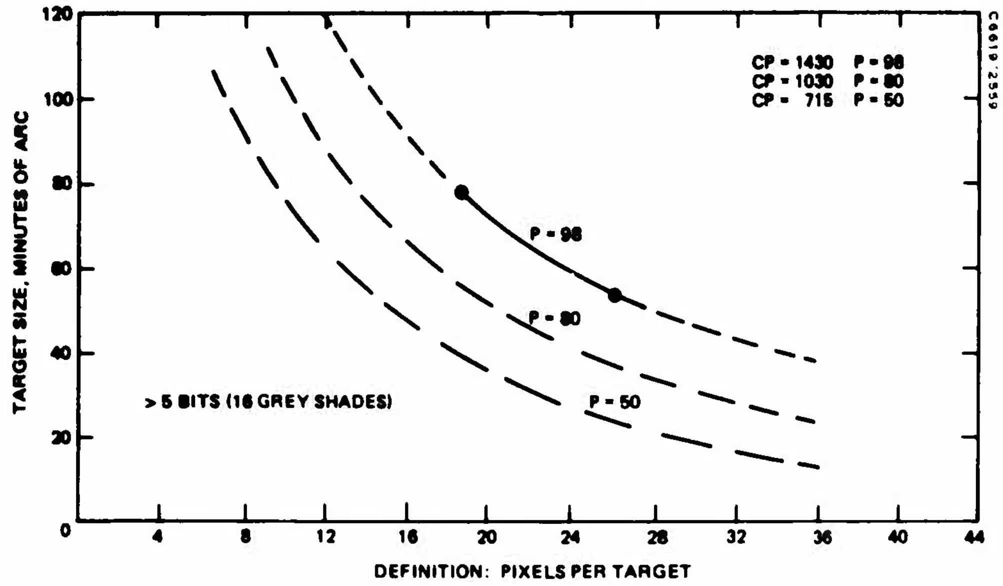
For this kind of task, if the size and scale factor of the display is fixed, it is clear that the higher resolution display (71 pixels per inch) yields better performance; recognition occurred when the target was 0.44 inch in size for the high resolution as compared to 0.63 inch size for the low resolution. This implies that a target will be recognized at greater range with the high resolution display.

If on the other hand, there are no constraints on the display size, better performance will be obtained with the coarse resolution display

(34 pixels per inch). The data show that 22 pixels across the target are required when the coarse resolution is used, but 31 pixels are required for the high resolution display. In these circumstances, the target will be recognized at longer range with the coarse resolution display.

The most convenient hypothesis to account for these paradoxical data is one that involves both the MSF of the eye and the cognitive demand, i.e., the amount of information needed to reach a conclusion about the object being viewed. With the high resolution display viewed in the experimental conditions described, each pixel subtended 2 arc minutes and with the coarse resolution 4 arc minutes. This corresponds to 15 and 8 cycles per degree respectively. Examination of the psychophysical MSF data show that the modulation required for a 15 cycle (30 pixel) image is considerably greater than that for the 8 cycle (16 pixel) image. This implies that the small modulations between individual pixels can be more easily discriminated visually when the pixel size conforms to the spatial frequency where the luminance threshold is lowest, i.e., 16 pixels per degree. The coarse resolution display satisfies that visual condition, and the limit to recognition performance is therefore contingent on the amount of information provided the operator. In these experiments, the recognition task of the operator required about 22 pixels (10 line pairs) across the major axis of the target. Targets were not recognized with the high resolution display (30 pixel/ degree) when the same number of pixels were laid across the target. This is probably because a spatial frequency of 30 pixels per degree requires more modulation for discrimination than does 15 pixels, and the required modulation did not exist in the target images.

These preliminary results suggest a constant product rule first proposed by Erickson (1970) that within limits, may be used in display design tradeoffs. This rule says that equivalent performance will be achieved when the product of target size and definition is constant. Target size is expressed in minutes of arc subtended at the observer's eye and definition as the number of pixels per target major axis. For the case in hand, the constant product for high probability of recognition and at least 32 grey shades equals 1430. Using the data from this pilot study and some corollary assumptions, a plot of various probabilities of recognition as a function of target subtense, pixels per target, and grey scale quantization has been constructed and is shown in Figure 3-15. The circles indicate data points and the dotted lines extrapolations. These curves should be considered as working hypotheses that require further empirical confirmation.



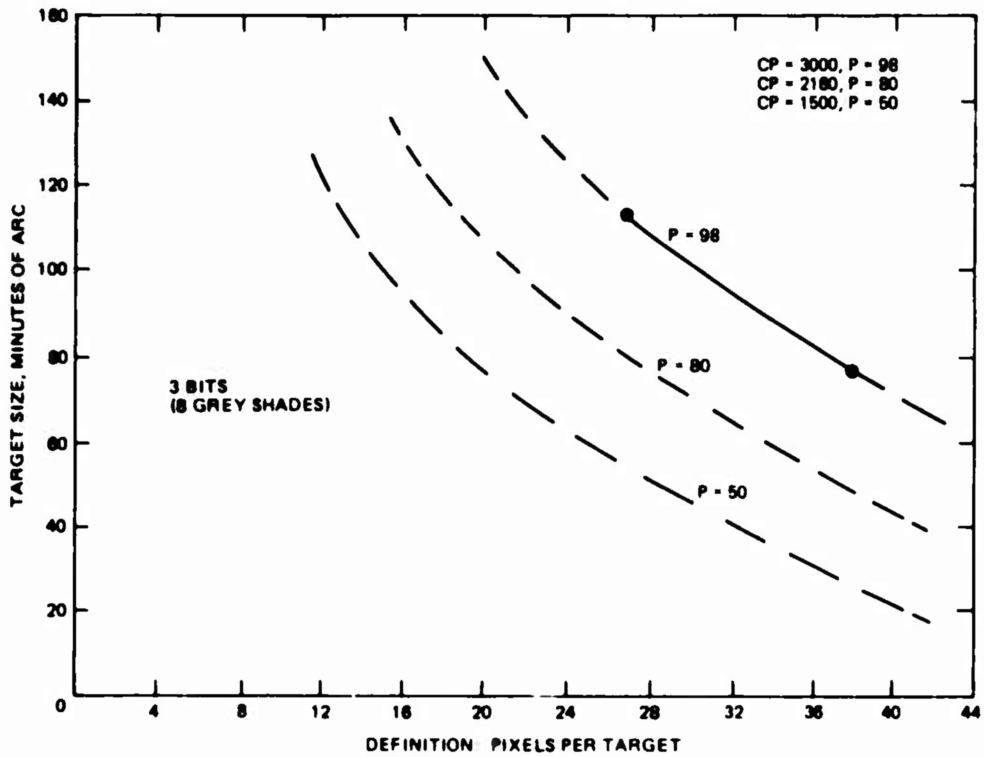


Figure 3-15. Constant product criteria indicating probability of recognition as a function of target size, definition, and gray scale quantization.

4.0 ANALYSIS OF DISPLAY MECHANIZATION PERFORMANCE CRITERIA

4.1 INTRODUCTION AND BACKGROUND

There are three major elements or functions of a display system; the display surface which provides the image to the observer, the storage medium which determines the temporal characteristics of the image, and the processor which determines the spatial characteristics of the image. The manner in which these various elements relate to one another is to a large extent a function of the particular display implementation. For example, a direct view storage tube combines within one envelope, the display surface and the storage characteristics; while a system utilizing an analog scan converter separates the display surface and the storage medium. Whatever mechanization is employed, each of the functional elements can be separately treated for analysis purposes. It is the purpose of this section to develop the analytical tools to evaluate each of these functional elements.

The requirements for the display surface by and large must be determined through an understanding of the operator requirements. Parameters such as display size, resolution, gray scale, brightness, contrast, and uniformity, must be specified to meet the demands of the operator for a specified task. Whether or not a storage medium is required and how much or how long the storage should be is related to the sensor update rate. If the sensor information is updated at a rate above the flicker frequency, then little or no storage is required except to provide freeze capability. Generally, storage is required when the sensors have low update rates such as those encountered in radar systems, line scanning infrared systems and air-to-air search and track infrared systems. The amount of storage required is dependent on the time required by the operator to perform in a satisfactory manner. The requirements can vary greatly as function of the task. For example, the detection of an airborne target is a completely different task than the detection of a ground target. The processing function in a display system is used to match the sensor parameters to a particular display system implementation. Items such as brightness transfer function and gamma correction, sampling, and coordinate conversion are all a part of the processing system.

Analysis of display performance, to be complete, must take into account all the possible techniques that can be used to implement the functions described in the preceding paragraphs. The criteria must cover designs which use; cathode ray tubes, direct view storage tubes, scan conversion tubes, digital processing and storage techniques, and matrix displays (light emitting diodes, liquid crystal, plasma, etc.).

At the present time, there is a major emphasis in the design of multi-sensor display systems using digital processing and storage techniques. The rapid development of digital technology and its demonstrated high reliability over the past few years has resulted in the specification of digital techniques for most advanced avionics systems. Another major development in display technology which will see increasing use in advanced systems is the flat panel matrix displays, such as light emitting diode arrays, liquid crystal elements, and plasma arrays, which provide images composed of discrete picture elements. These display devices are attractive primarily because of their low volume, low voltage, and low power operation as compared with CRT technology. These two technologies – digital processing and matrix displays – have one key common factor, the dividing up of the image into discrete elements.

Because of this emphasis on sampled data systems, this analysis will first be performed for digital scan converted display systems. The analysis of analog display mechanizations and the generation of specific design criteria based on the analytical work developed in this section will be provided in subsequent reports.

4.2 MAJOR DESIGN PARAMETERS

The main elements of a digital scan converter display system are shown in Figure 4-1. The key design parameters which must be specified for each element are listed below each functional block. A specific display system design is bounded on one end by the sensor characteristics and on the other end by the operator characteristics and mission performance requirements or task requirements, i.e., detect airborne targets or recognize a specific type of ground vehicle. The operator characteristics and the task requirements have the major influence on the design requirements for the display, such as size, resolution, brightness and contrast. The resolution requirement at the display determines the resolution requirements for the scan converter main memory, while the brightness and contrast requirements determine the dynamic range, gamma, and image enhancement requirements in the input and output processing.

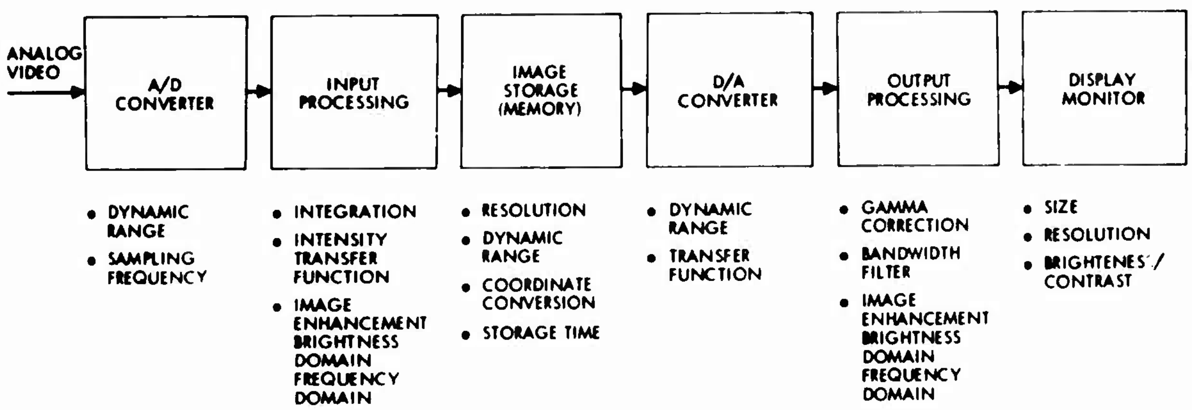


Figure 4-1. Major functional elements of the digital scan converter display system.

For purpose of the analysis in this section, the display is considered to be non-limiting to the sensor characteristics. Also, no analysis of image enhancement techniques is included in this present report but will be developed in future reports. The following analysis is directed at the following specific areas:

- Sampling frequency and its effect on the modulation transfer function of the sensor video
- Number of A/D converter bits and their effect on dynamic range and signal to noise (S/N) ratio

- Video integration and its effect on S/N ratio improvement
- Memory formatting and coordinate conversion and its effect on resolution
- Output D/A conversion and gamma shaping and its effect on dynamic range and discernable gray shades.

4.3 ANALOG TO DIGITAL CONVERSION

The A/D converter consists functionally of two components: a boxcar sampler and a digital quantizer. These are shown schematically in Figure 4-2. The boxcar sampler converts the analog signal to a train of pulses of duration τ, and the quantizer converts the continuous range of pulse amplitudes to a set of discrete levels. The net effect of the A/D converter is to change a signal continuous both in time and amplitude into a discrete signal in both dimensions. Both elements contribute to image noise by the act of quantization and therefore decrease system signal to noise ratio.

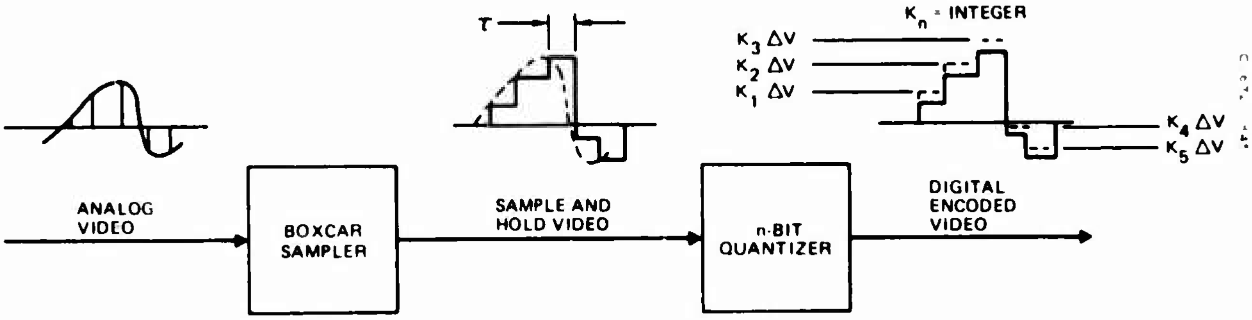


Figure 4-2. A/D converter.

The major noise source in a digital display system is the A/D converter. The A/D converter sampling rate also determines the modulation response of the display system,assuming the memory and display have sufficient memory capacity and resolution to store and reproduce all of the samples taken by the A/D. In this section, the effect of sampling and quantization on system MTF, dynamic range, and signal-to-noise ratio are discussed.

4.3.1 Sampling Rate

Sampled display systems should accurately reproduce the highest frequencies of interest in the sensor video for each display dimension while introducing a minimum of aliasing. The "highest frequency of interest" is first established for the sensor in terms of sensor parameters. This frequency represents the resolution limit of the sensor (f_o) and is defined at a point where increasing the frequency yields little meaningful sensor information. The sensor video is then assumed to be effectively bandlimited at f_o, and the Nyquist sampling criterion of at least two samples per cycle at the bandlimiting spatial frequency f_o is applied to derive the required number of samples.

The Modulation Transfer Function (MTF) of a sampled data system is a function of both the number of samples taken per cycle of input video and the phase relationship of the sampling pulse and the input video. A functional block diagram of the sampling process is shown in Figure 4-3. The average modulation over all phase angles can be computed analytically and is the magnitude of the Fourier transform of the rectangular pulse response of the boxcar sampler or the function: $\left|\frac{\sin \pi x}{\pi x}\right|$, where x is the ratio of input frequency (N) to sampling frequency (M).

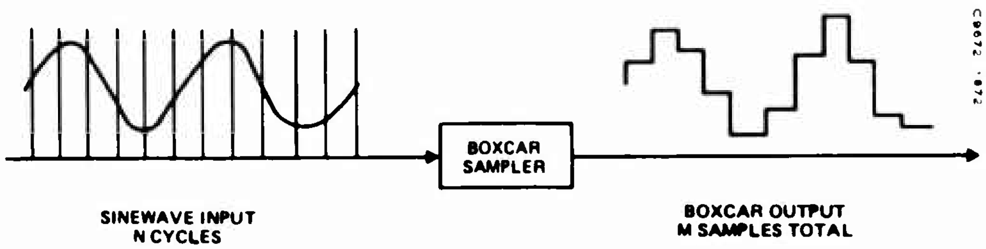


Figure 4-3. Sampling system.

The maximum and minimum modulation for a specific phase relationship can also be calculated. These three functions; maximum modulation, average modulation, and minimum modulation; are plotted in Figure 4-4.

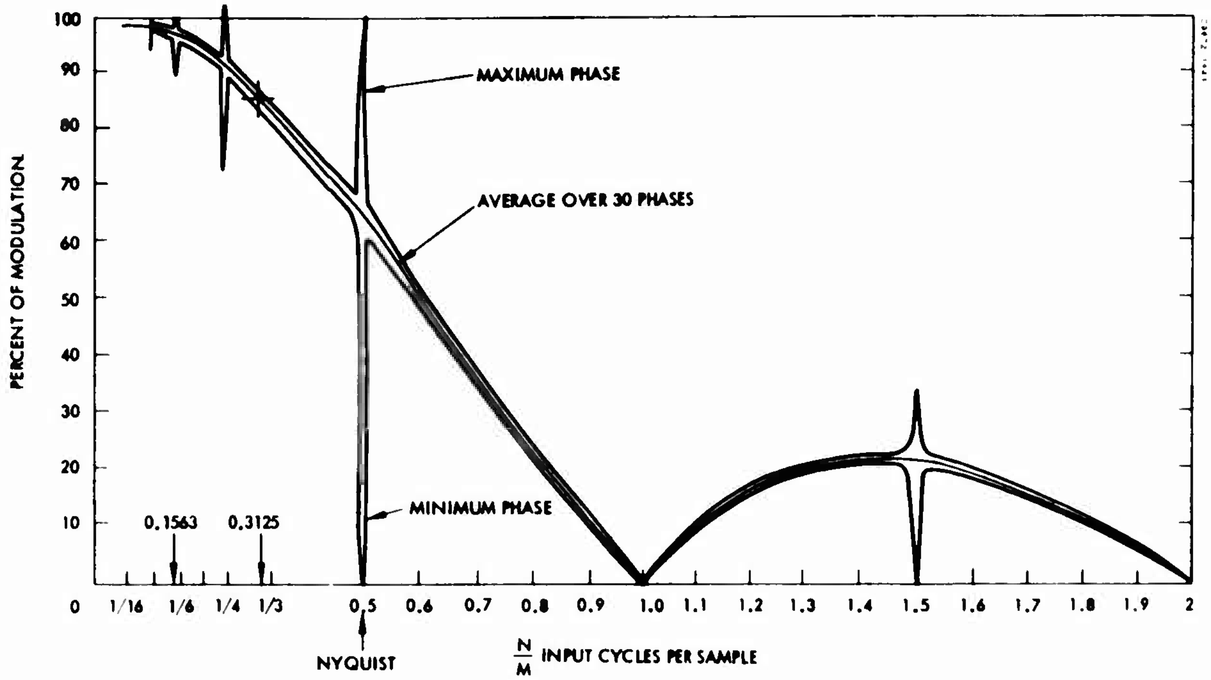


Figure 4-4. A/D converter MTF.

Nyquist sampling is represented by $N/M = 1/2$, at which point the average modulation is $2/\pi \approx 65$ percent. There is also a maximum variation of modulation with phase, since the minimum modulation is 0 percent and the maximum modulation is 100 percent. Input frequencies such that $N/M > 1/2$ are subject to aliasing, which means that although the output modulation may be greater than zero, it will be at a lower frequency than the input, resulting in distortion of information.

The singular behavior of the maximum phase curve as $N/M \rightarrow 0$ is explained as follows. For $M/N = 2K$, where K is any positive integer, i.e., for an even number of samples per cycle, there exists a phase for which one sample is taken just at the peak of the sinusoid, and another sample is taken just at the minimum, giving 100 percent modulation for that phase. On the other hand, for M/N odd, if one sample is taken at the peak of the sinusoid, then the following minimum is symmetrically straddled by a pair of samples, so the modulation is less than 100 percent. A similar discussion applies to the minimum phase curve, where there always exists a phase for which two samples are zero if M/N is even, and only one sample can be zero if M/N is odd. As the number of samples taken per cycle becomes large, i.e., as $N/M \rightarrow 0$, the effect of one or two individual samples becomes unimportant, so the singularities decrease in amplitude, and all the curves converge to $|\sin \pi x/\pi x|$.

These results can be applied to the computation of display system sinewave MTFs. The magnitude portion of the MTF of a system which is a cascade of several components is the pointwise product of the magnitudes of the MTFs of each of the components in the system. Thus, the display system MTF is multiplied by the sensor MTF to determine the overall system MTF. The display system MTF is the product of the sampler MTF, the processor MTF, and the display MTF. Since the digital memory is discrete in nature beyond the sampler, the memory MTF, $M(f) = 1$ for all frequencies f passed through the sampler. In other words, there are no further MTF losses beyond the sampler due to the memory in a display system, if sufficient memory elements are provided to store and display all the samples taken. It is also assumed the D/A has a much wider bandwidth than the rest of the system.

A complete display system MTF is the combination of the cascaded A/D converter, video integrator, and display. The MTF in Figure 4-4 can be converted to a more standard form as follows. Each cycle represents a line pair. There are n resolution bins in a line, say, for a k-inch display. Then

$$\frac{\text{Input cycles}}{\text{Sample}} \times \frac{\text{1 line pair}}{\text{Input cycle}} \times \frac{n}{k} \frac{\text{samples}}{\text{in.}} = \frac{n}{k} \frac{\text{line pairs}}{\text{in.}} .$$

For example suppose a CRT has a 0.010-inch half-amplitude gaussian spot size. A modulation transfer function for this CRT is shown in Figure 4-5. Assume 768-resolution element samples across a 10-inch rectangular display. Combination of the two MTFs by multiplication is shown in Figure 4-5, which represents the display system modulation transfer characteristic.

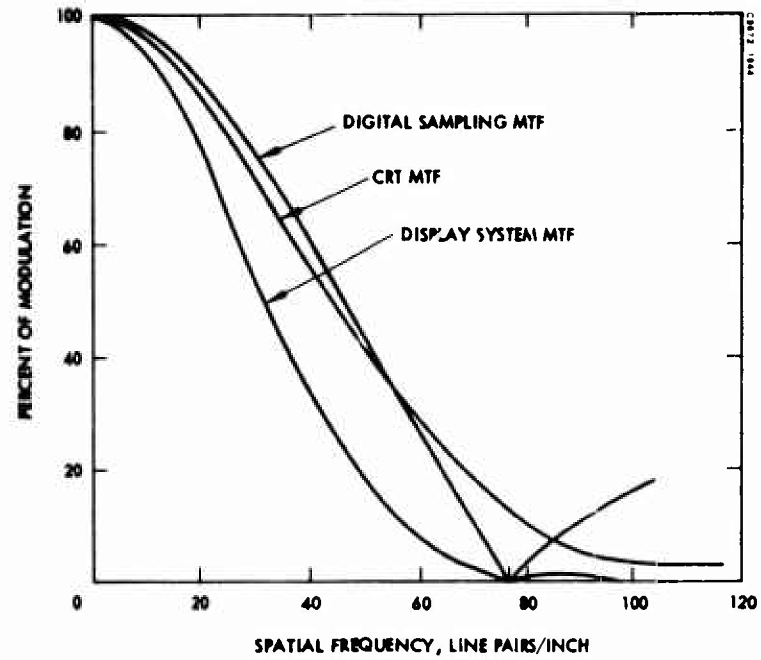


Figure 4-5. DSC/display system sine wave MTF.

4.3.2 A/D Converter Dynamic Range

Once the A/D sampling rate is determined, based on the frequency response of the sensor video, the other major design parameter for the A/D is the number of bits required to encode the video dynamic range. Assuming the A/D converter is a linear process which produces a binary output whose magnitude is linearly related to the magnitude of the analog input voltage, then if V_{min} is the minimum voltage quantization and V_{max} is the maximum voltage quantized

$$V_{MAX} = 2^n V_{MIN} \quad ,$$

where n = the number of A/D bits. The dynamic range of the video is by definition

$$K = 20 \log_{10} \frac{V_{max}}{V_{min}} = 20\, n \log_{10} 2 = 6.02\, n \text{ (db)}.$$

Therefore, the dynamic range of the A/D converter is equal to approximately 6 dB times the number of A/D bits. This relationship is tabulated in Table IV-1. Conventional television displays have dynamic ranges of 25 to 30 dB for example, thereby requiring 4 to 5 bits of dynamic range encoding.

TABLE IV-1. DYNAMIC RANGE AS A FUNCTION OF A/D BITS

n	Dynamic Range = K (dB)
1	6.02
2	12.04
3	18.04
4	24.08
5	30.10
6	36.12
k	6.02 k

4.3.3 Sampling Noise

This noise is introduced by quantization in time. Information is lost between sample points and, intuitively, the sampling pulse width should be kept small to avoid distortion of the sampled signal frequency spectrum.

The input signal transform is multiplied by the sample and hold circuit transform with a resultant system transfer function as shown in Figures 4-6 and 4-7. Mathematically, the system transform,

$$X_s^h(f) = X_s(f)\ H(f).$$

If the sample pulse time is short with respect to the sample spacing, i.e., $\tau << 1/2\omega_s$, or $1/\tau >> 2\omega_s$, the Fourier spectrum of $X_s^h(t)$ is as shown in Figure 4-6. Observe that in this case, the sample and hold transfer function, H(f) is much wider than the input transfer function and therefore the input signal is not appreciably distorted from that of $X_s(f)$, which is identical to

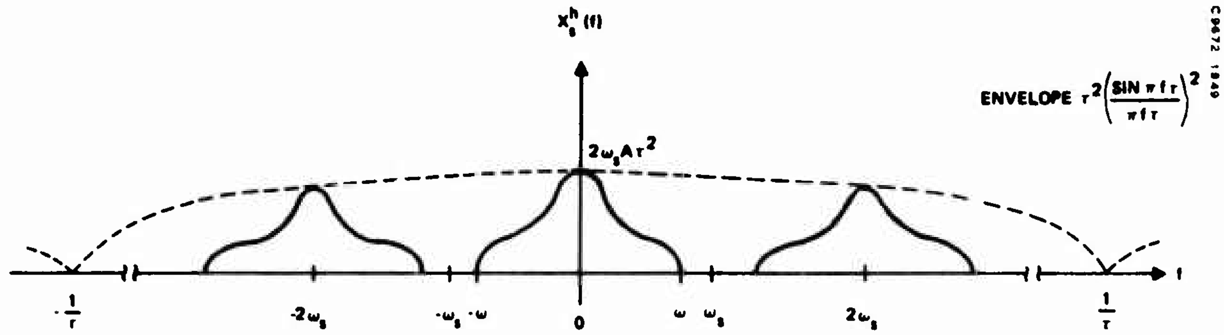


Figure 4-6. Sampled signal spectrum, short hold pulse.

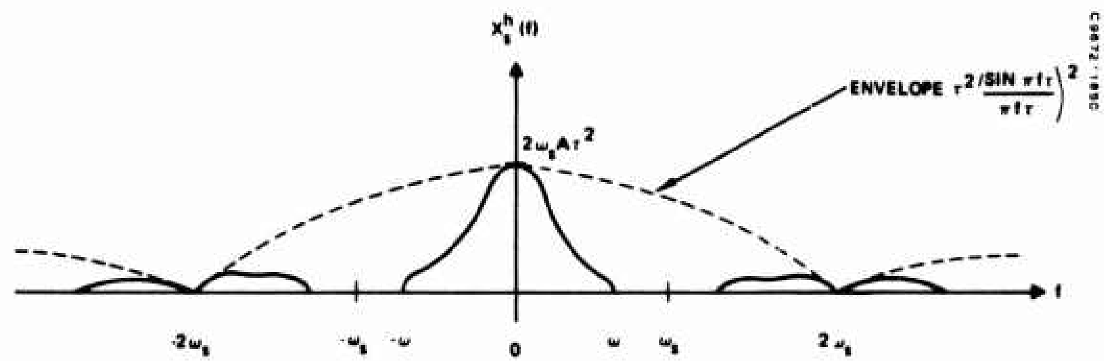


Figure 4-7. Sampled signal spectrum, long hold pulse.

the input spectrum X(f). The reconstructed signal will be close to the original input signal X(t). However, now consider the case where the pulse width is equal to the sample spacing, i.e., $\tau = 1/2\omega_s$ or $1/\tau = 2\omega_s$. Then the Fourier spectrum of $X_s^h(f)$ is shown in Figure 4-7. Note in this case that the sample and hold transfer function, H(f), is now roughly comparable in width to the input, $X_s(f)$, so that $X_s^h(f)$ is significantly distorted from that of $X_s(f)$, particularly at the higher frequencies. This means that edge and detail information can be attenuated appreciably in the reconstructed signal X(t). Hence in this type of sampling, it is desirable to minimize the hold pulse duration.

The noise power introduced by the sample and hold process is

$$P_s = \int_{-\omega_s}^{+\omega_s} \left| X(f) - X_s^h(f) \right|^2 df,$$

where X (f) is the spectrum of the input signal and X_s^h (f) is the spectrum of the signal at the output of the boxcar sampler. Since

$$X_s^h(f) = X_s(f)\ H(f) \qquad ,$$

where

$$H(f) = \tau \left(\frac{\sin \pi f \tau}{\pi f \tau} \right) \qquad ,$$

and

$$X_s(f) \equiv X(f)$$

for

$$\left| f \right| \leq \omega_s$$

if the Nyquist sampling criterion is satisfied, we have

$$P_s = \int_{-\omega_s}^{+\omega_s} \left| X(f) - X(f)\ H(f) \right|^2 df = \int_{-\omega_s}^{+\omega_s} \left| X(f) \right|^2 \left| 1 - H(f) \right|^2 df \quad .$$

The noise introduced by sampling is seen to be a function of the input signal frequency spectrum and the sample pulse width, assuming the Nyquist sampling criteria is satisfied.

4.3.4 Quantization Noise

Assume an n-bit quantizer in the A/D converter. Then the input signal will be broken into 2^n discrete amplitude levels. Assume further that the input pulse train has amplitudes which are equally likely over the range of the converter. Since the uniform distribution represents a worst case situation, analysis with realistic input amplitude distributions should yield larger SNRs. The quantization errors q are uniformly distributed, and their variance, is

$$\sigma_q^2 = \frac{2^{-2n}}{12} \quad .$$

The noise power due to quantization, assuming a stationary noise process and a nearest level quantizer with a mean noise level equal to zero is therefore

$$P_s = \sigma_q^2 = \frac{2^{-2n}}{12} \quad .$$

4.3.5 Total Noise

The noise power due to the cascading of the two elements of the A/D converter are arrived at by summing the power of each. The RMS noise for the system is thus

$$P_{RMS_{A/D}} = \left[\frac{2^{-2n}}{12} + P_S\right] ,$$

since time quantization and amplitude quantization are independent, random processes.

Given an input signal with signal to noise ratio S_i^2/σ_i^2, where σ_i^2 represents the input noise power, and S_i^2 represents the RMS power of a deterministic signal, the output noise variance is given by

$$\sigma_0^2 = \sigma_i^2 + \frac{2^{-2n}}{12} + P_s \quad ,$$

and computing the output SNR,

$$\left(\frac{S}{N}\right)_0 = \frac{S_i^2}{\left[\sigma_i^2 + \frac{2^{-2n}}{12} + P_s\right]} = \frac{S_i^2}{\sigma_i^2}\left[1 + \frac{1}{12}\left(\frac{2^{-n}}{\sigma_i}\right)^2 + \frac{P_s}{\sigma_i^2}\right]^{-1} .$$

The change in input SNR expressed in dB is thus

$$\Delta SNR \triangleq \left(\frac{S}{N}\right)_0 - \left(\frac{S}{N}\right)_i$$

and

$$\Delta SNR = -10 \log_{10}\left[1 + \frac{1}{12}\left(\frac{2^{-n}}{\sigma_i}\right)^2 + \frac{P_s}{\sigma_i^2}\right] \quad .$$

The signal to noise ratio decrement is a function of both the quantization interval and the sampling process. Figure 4-8 shows a plot of ΔSNR as a function of the second term in the last equation with the third term in the equation for ΔSNR as a parameter. Thus, Figure 4-8 may be used to determine the degradation in signal-to-noise ratio from the sampler and the quantizer.

Assuming a nominal value of 1.5 for the ratio of the quantization interval to input noise standard deviation and a sampling noise power of one-quarter of the IF noise variance, a loss in SNR of 1 dB due to A/D conversion is experienced.

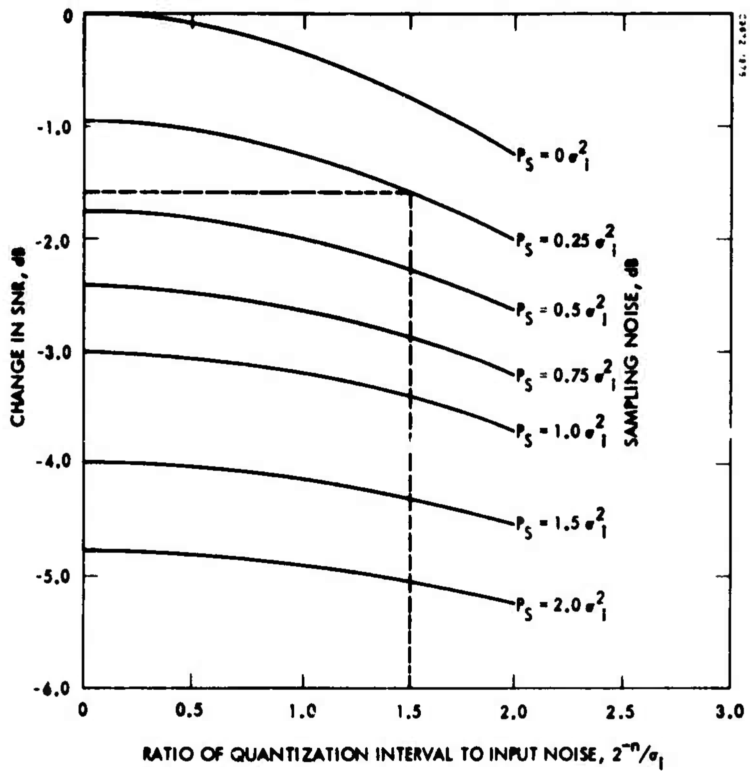


Figure 4-8. Effect of digitization on system signal-to-noise ratio.

4.4 DIGITAL VIDEO INTEGRATOR

An integrator in the digital display system can be used to improve the signal to noise ratio of the video. It can be used in a number of different ways and applied to several sensors. For example, for a FLIR sensor with a high frame rate, integration from frame to frame may be desirable. Also in a low PRF B-scan radar mode, the integrator can be used to collapse the several thousand input sweeps in one radar scan to the few hundred necessary to preserve resolution. Used in this way, the signal to noise ratio improvement results in better operator target detection performance. In fact, target detection studies performed at Hughes have indicated that targets as small as 3 db below the residual noise level could easily be detected when stored and displayed in a B-scan format through a digital scan converter with a video integrator at the input.

A block diagram of a line-by-line digital integrator is shown in Figure 4-9. It consists basically of a serial shift register memory to hold the accumulated sum of the video as it is shifted in element by element. Every time a new range sweep is clocked into the system, the stored sum is reduced by a multiplying factor in a feedback loop and added element by element to the new quantized video.

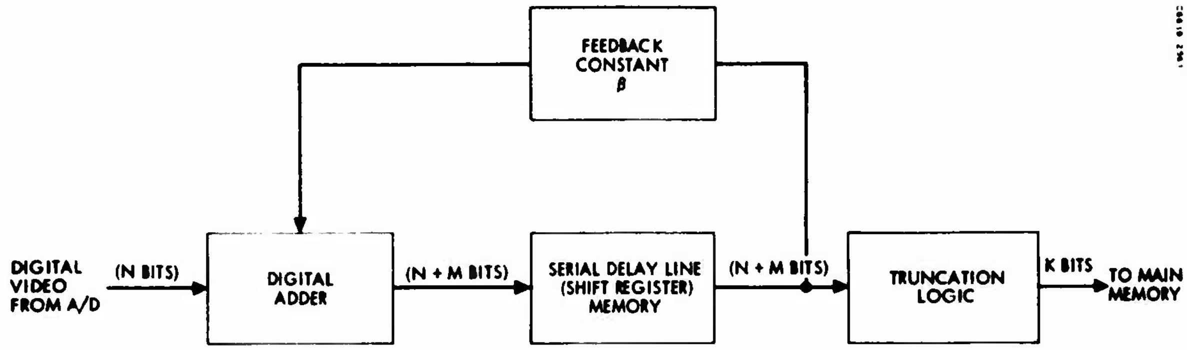


Figure 4-9. Digital video integrator.

When the accumulated sum is transferred to the main memory, it is necessary to truncate it to the number of bits stored. This truncation logic can be achieved by simply transferring the most significant bits or by providing a special logarithmic truncation function. Besides the truncation technique, two other integrator parameters significantly affect the integrator performance. These are the number of bits carried in the integrator and the feedback constant. The number of bits carried directly affects the dynamic range of the integrator and the feedback constant relates to the effective time constant of the integrator. By proper selection of these parameters, the integrator can provide a significant increase in the signal-to-noise ratio of the digital video.

The video signal-to-noise ratio improvement figure is developed as follows (Cooper and Griffiths, 1961):

$$F = \frac{1}{\sqrt{\phi}} \sqrt{\frac{\pi}{2}}\, e^{-\theta_N^2} \sqrt{-q}\, e^{\left(\frac{q}{2} + \theta_N\right)^2} \left[1 + \operatorname{erf}\left(\frac{q}{2} + \theta_N\right)\right] \quad ,$$

where

$$q = \frac{\ln^{\beta}}{\phi} \quad ,$$

and

$$\frac{q}{2} + \theta_n \geq 0 \quad .$$

This is plotted in Figure 4-10. Note that as the magnitude of q decreases, the signal to noise ratio increases until $|q| = 0.70$, at which point the signal to noise ratio begins to decrease again. Thus to maximize the output signal to noise ratio,

$$q = -0.70 \quad .$$

Since

$$q = \frac{\ln^{\beta}}{\phi}$$

and

$$\phi = \frac{\Gamma}{M} \quad ,$$

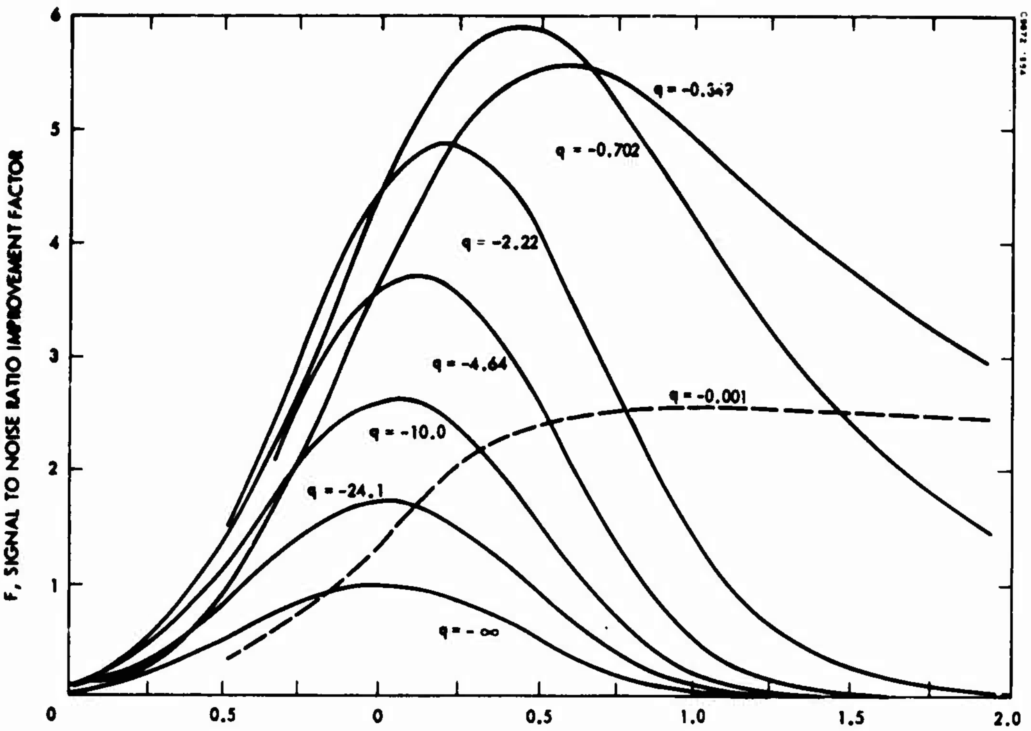


Figure 4-10. S/N ratio improvement.

where Γ is the antenna 3 db beamwidth and M is the number of samples taken between the 3 db points, then the feedback constant $\beta = e^{-0.7\,\Gamma/M}$. This relationship is plotted in Figure 4-11 for a beamwidth of $\Gamma = 2.00$ degrees.

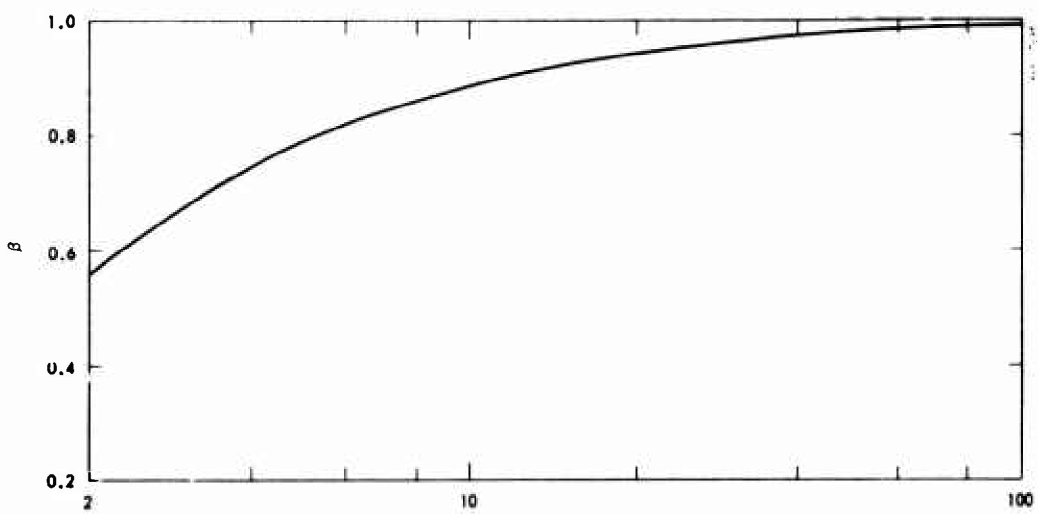


Figure 4-11. Optimum feedback constant β.

To prevent saturation of the integrator, sufficient bits to encompass the accumulated integrator sum must be provided. The total bits required are N + M where N is the initial digital video bits from the A/D converter and M is the additional bits required in the integrator to handle the total accumulation of summed video. The additional bits required are a function of the feedback constant, β, and are determined from the following expression:

$$M = \log_2 \frac{1}{1 - \beta}$$

or

$$\frac{1}{1 - \beta} = 2^M .$$

For example, if β = 7/8, then 1/1-β = 8 and M = 3. If the initial input bits from the A/D were N = 4 bits, then the total number of bits in the adder and integrator memory must be N + M = 4 + 3 = 7.

4.5 MEMORY CONSIDERATIONS

The most important design decisions required in the development of a digital display system involve the digital memory. These include not only the considerations which determine the type of digital memory, but also the formatting of the data stored for ease of read-out and display. A memory can be formatted and read out in one of two ways. The first is to store the sensor video sequentially in the memory as it is received from the sensor and achieve the various formats by formatting the display sweeps upon readout. This approach uses simple memory addressing logic, but requires high power linear deflection amplifiers in the display indicator. The alternate way is to always read the memory out in a horizontal television raster format thereby requiring complex memory load address generation but permitting the use of a lower power resonant deflection TV indicator. It also provides for simple recording of the video and establishes a standardized interface such as EIA standards RS 170 and RS 343. A standard orthogonal raster readout will also probably be required for future matrix addressable flat panel display techniques.

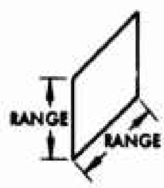
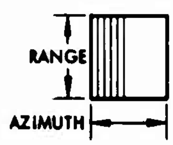
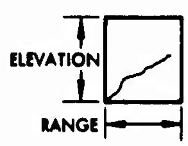
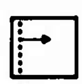
A summary of the basic formats to be handled in the digital scan converter are shown in Table IV-2. Also tabulated is the function of the digital scan converter for each of these formats; that is rate conversion (slow scan to fast scan) or format conversion (PPI to TV). Obviously the freeze mode is provided for all formats. Some of the unique characteristics of these various modes will now be discussed.

4.5.1 Coordinate Conversion

In the B-scan, E-scan, FLIR, or TV modes, there is no difference in image quality or display appearance for either a TV raster or linear display format since both represent an orthogonal transformation or mapping of the sensor data to the display surface. However, in the PPI modes, there is a major difference in the transformation of the data from the radar to the display surface as a function of whether a TV raster or PPI format is generated on the display. Whether this results in a significant difference in image quality or display appearance depends on the radar resolution characteristics and the DSC spatial quantization. The TV raster display presentation is characterized by constant Δ_X and Δ_Y resolution elements, where Δ_X is the display width divided by the number of horizontal samples and Δ_Y is the display height divided by the number of television scan lines.

The linear sweep PPI format provides constant range and angular resolution elements, Δ_R and Δ_θ, where Δ_R is the range scale divided by the number of range samples and Δ_θ is the azimuth scan width divided by the number of azimuth samples. Radar resolution is defined in terms of the pulse width in range and the antenna beamwidth in angle and therefore corresponds to the linear sweep format resolution parameters. The TV raster resolution parameters must, therefore, be converted to equivalent radar resolution elements in order to compare the performance of the two systems.

TABLE IV-2. SUMMARY OF BASIC DISPLAY FORMATS

SENSOR MODE	FORMAT	DSC FUNCTION	
		TV MONITOR	LINEAR MONITOR
RADAR			
PPI		COORDINATE CONVERSION AND RATE CONVERSION	RATE CONVERSION ONLY
SIDELOOKING		COORDINATE CONVERSION AND RATE CONVERSION	RATE CONVERSION ONLY
B-SCAN		COORDINATE CONVERSION AND RATE CONVERSION	RATE CONVERSION ONLY
E-SCAN		RATE CONVERSION ONLY	
FLIR			
DISCOID (TV RASTER)		REQUIRED FOR FREEZE ONLY	
SCANNED MULTI-DETECTOR ARRAY		REQUIRED FOR FREEZE AND COORDINATE CONVERSION	
TELEVISION			
		REQUIRED FOR FREEZE ONLY	

Basic assumptions for the analysis were: 1) a square display and 2) an array of b x n memory bins, or elements, on the display (x and y axes, respectively). For the sake of generality, the display is considered to be a 180 degrees offset sector plan position indicator (PPI) with the 0.0 degree azimuth coincident with the +X axis. To obtain consistency of results, it was assumed that the azimuth and range uncertainties are centered about a bin, since the address of an element anywhere within a bin will cause a response throughout the bin. The resulting geometry is illustrated in Figure 4-12. Quantization of range and azimuth angle is performed prior to the transformation. Given an element at arbitrary range, R, (inches on display) and azimuth θ, the display range and azimuth resolution is given by the following expressions:

$$\Delta R = \begin{cases} \dfrac{\sec \theta}{m}, & 0 \le \theta \le \theta_{CRIT \cdot R} \\[2ex] \dfrac{\csc \theta}{n}, & \theta_{CRITR} \le \theta \le \pi - \theta_{CRIT \cdot R} \end{cases} \qquad (4\text{-}1)$$

$$\theta_{CRIT \cdot R} = \arctan \frac{m}{n}$$

$$\Delta\theta = \begin{cases} 2 \arctan \dfrac{1}{2n \frac{R}{K} \cos \theta} & \theta \le \theta \le \theta_{CRIT \cdot AZ} \\[2ex] 2 \arctan \dfrac{1}{2m \frac{R}{K} \sin \theta} & \theta_{CRIT \cdot AZ} \le \theta \le \pi - \theta_{CRIT \cdot AZ} \end{cases} \qquad (4\text{-}2)$$

$$\theta_{CRIT \cdot AZ} = \frac{\pi}{2} - \theta_{CRIT \cdot R} = \arctan \frac{n}{m}$$

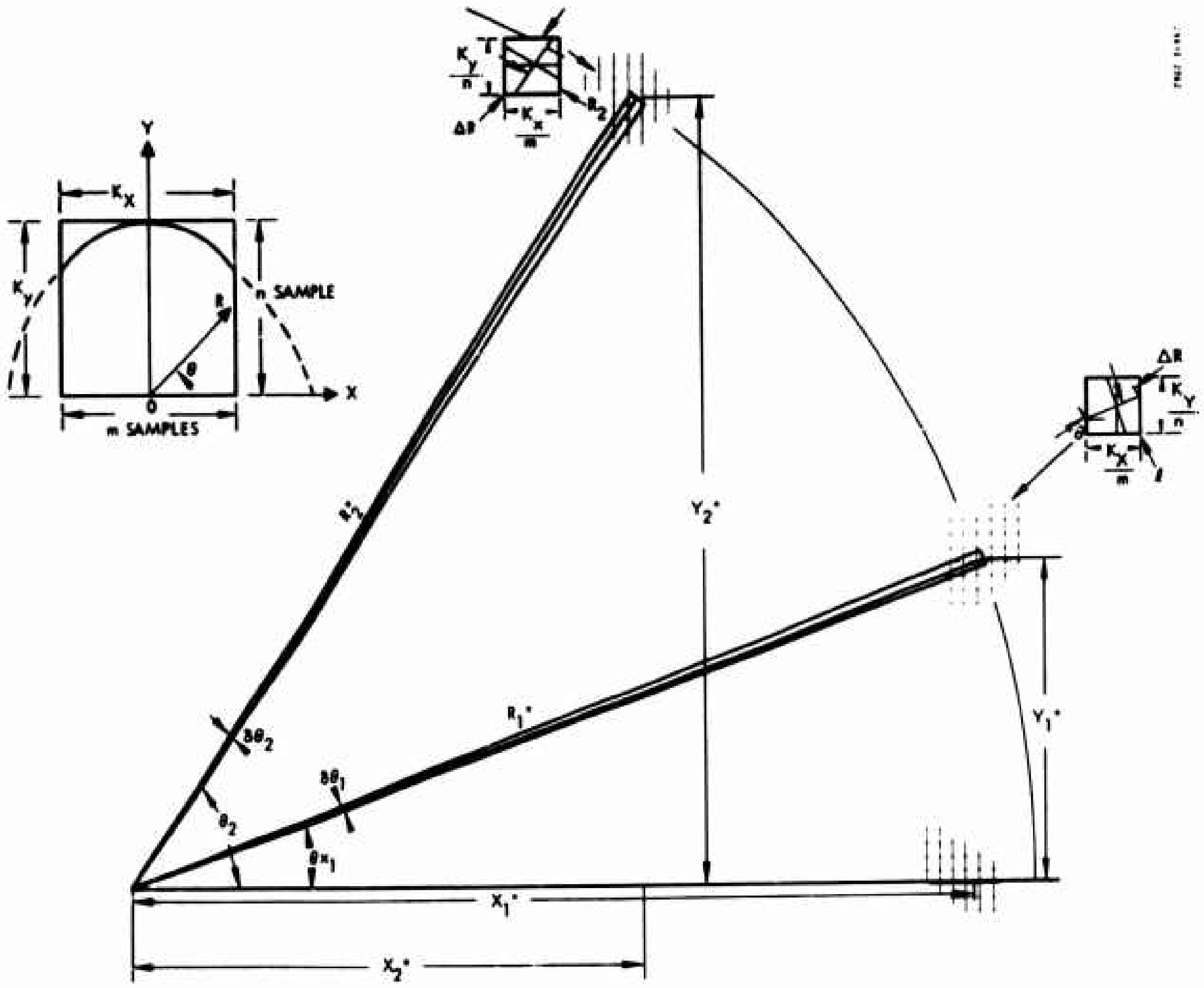


Figure 4-12. Display geometry: PPI on a digital rectangular display.

The azimuth resolution at $\theta = 0$ degrees as a function of the number of vertical samples, n, for various R/K ratios is plotted in Figure 4-13. For example, to provide a resolution element of 3 degrees at a minimum of 10-percent range on the display requires approximately 192 samples or resolution elements across the display.

The locus of equal-angle resolution elements is a rectangle about the vertex of the PPI format as shown in Figure 4-14. By plotting the locus of points representing the Nyquist sampling resolution, and computing the percentage of total display area that provides greater resolution than Nyquist sampling, another performance criteria can be established to determine the number of samples required for a specific system. This is

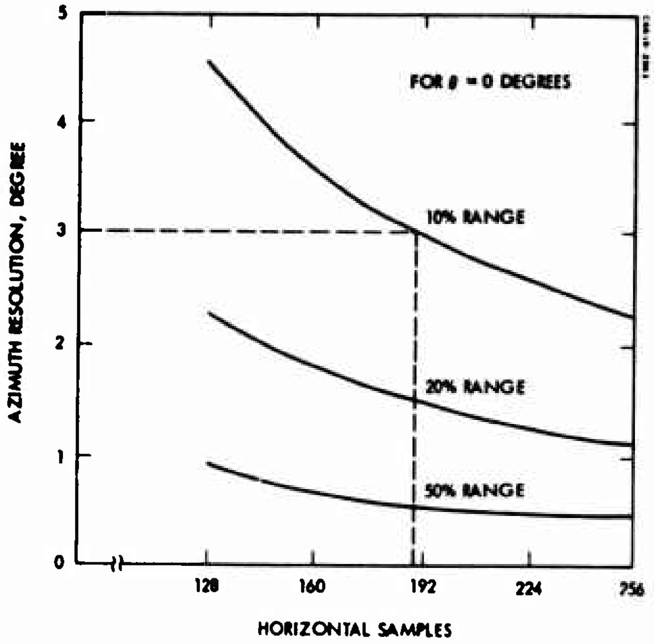


Figure 4-13. Azimuth resolution versus number of vertical samples for θ = 0 degrees.

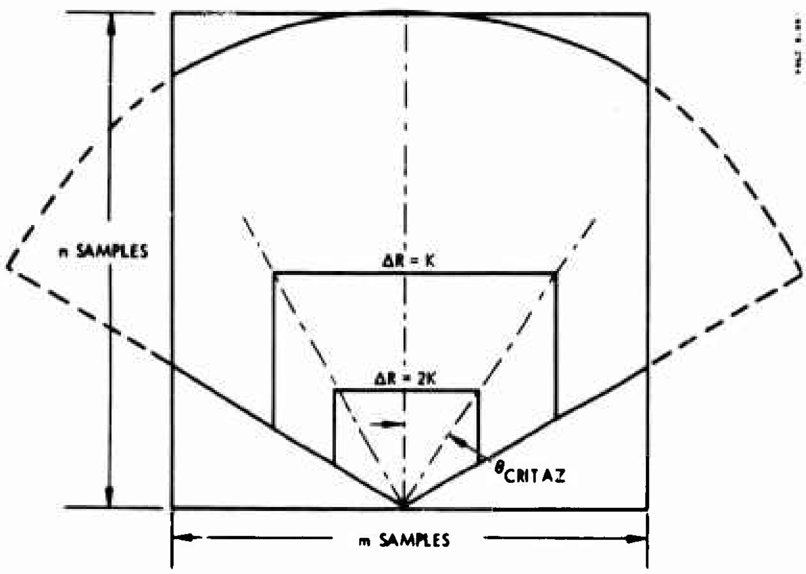


Figure 4-14. Locus of equal-angle resolution elements.

plotted in Figure 4-15 as a function of the ratio of display horizontal samples m (assuming m = n) to the number of Nyquist samples in a scan width for various scan widths.

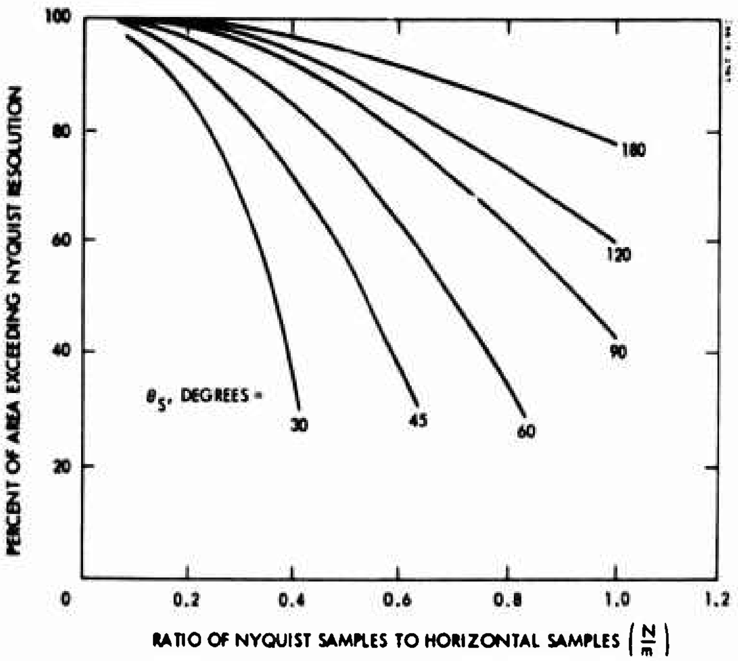


Figure 4-15. Percent of display area that exceeds Nyquist azimuth resolution as a function of ratio of Nyquist samples to horizontal samples for various scan widths.

The range and azimuth resolutions were also computed for a typical PPI display format with a 120-degree sector scan and a 256- by 256-resolution element display. The results are shown in Figures 4-16 and 4-17.

4.6 DIGITAL TO ANALOG CONVERSION

The digital video, once stored in the memory, does not vary and is a linear representation of the video received element by element from the sensor (assuming linear A/D conversion). Since cathode ray tubes and the human visual system are more or less operationally limited to approximately 11 shades of gray, it is impractical and inefficient to store more than 4 bits.

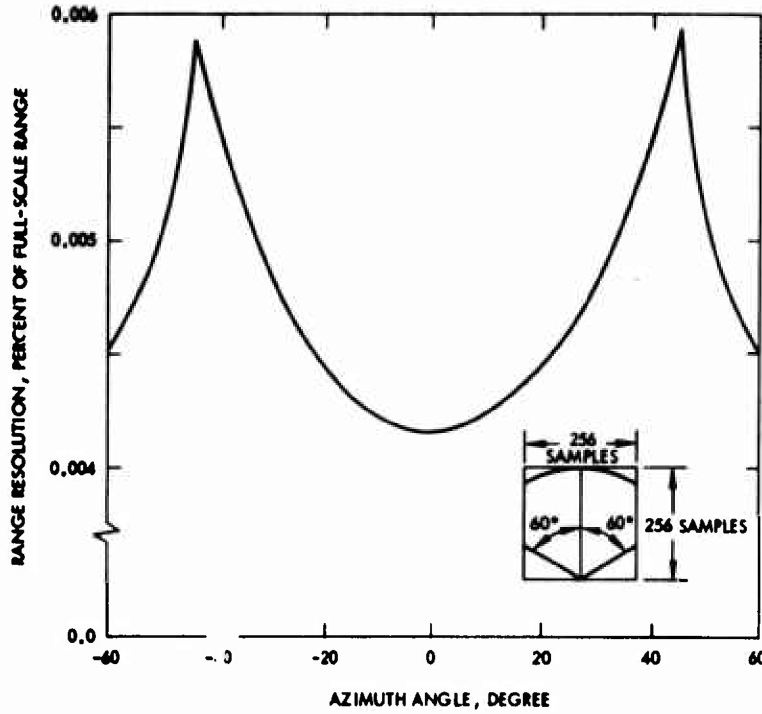


Figure 4-16. PPI range resolution as a function of range and azimuth for a 256 x 256 sample display.

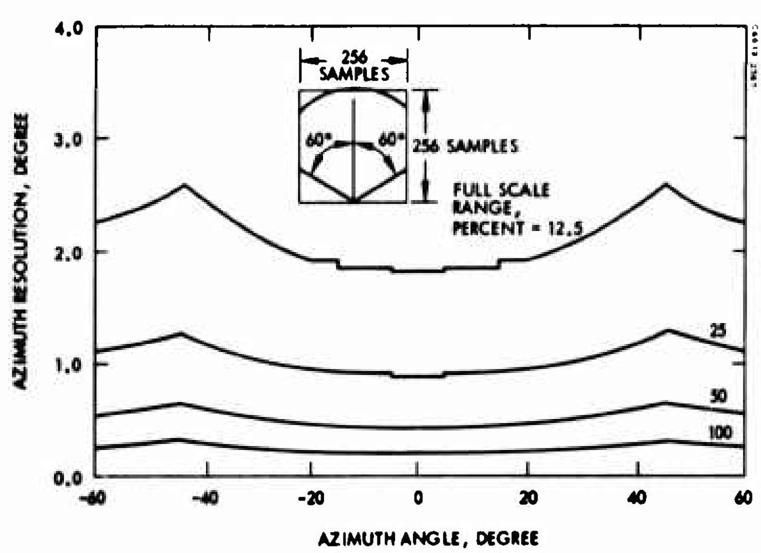


Figure 4-17. PPI azimuth resolution as a function of range and azimuth for a 256 x 256 sample display.

In fact, 3 bits is sufficient for many cases and indeed even 2 bits may be sufficient for most detection purposes. The important consideration is the rendition of the discrete levels stored to maximize the number of discernible gray shade levels displayed. With a totally linear display system, the 4 bits are linearly D/A converted, and the resultant analog voltage drives the display CRT in the manner shown in Figure 4-18. (Assuming operation in the linear region of the CRT transfer curve.) Since the dynamic range of a linear 4-bit system is only 15:1, only about 6 shades of gray can be displayed at a time. This is because each successive higher gray shade must be at least 1.4 times brighter than the next lowest to be easily discriminable. (1.4 is a nominal value, actually the required contrast is a function of resolution, brightness level, and other factors.) With only 6 discernible shades of gray, optimum utilization of the 16 stored energy levels is not being achieved. Also, the gray scale capability of the observer and display is not used. To maximize the information content, each successive gray scale level should be displayed with 1.4 times the brightness of the previous one.

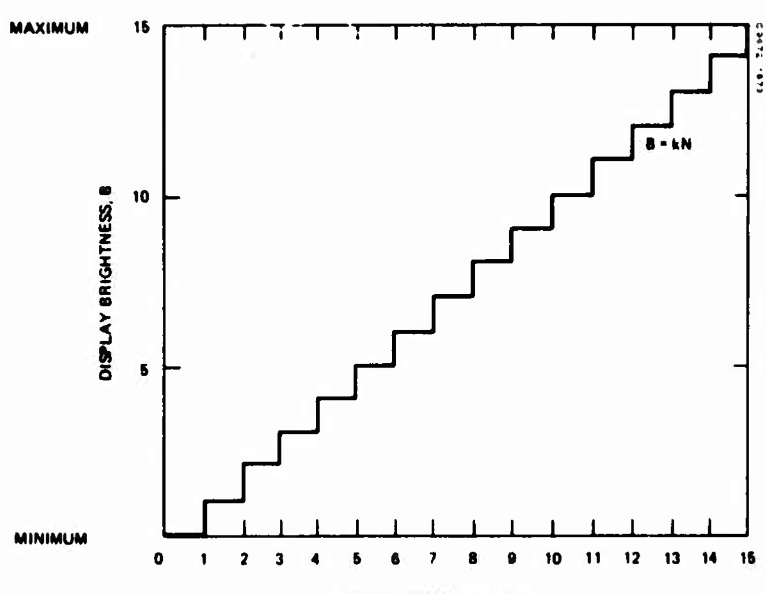


Figure 4-18. Sample of a linear gamma.

To provide the required transfer function (gamma) to convert from the elemental stored energy levels in the digital scan converter memory to a maximum number of discriminable gray shades on the CRT, a non-linear transfer network is required. This can be either digital logic prior to D/A conversion or analog circuitry afterward. The digital mechanization is preferred, because digital circuitry is less susceptible to drift, requires no adjustment, and hence requires minimum maintenance and provides a lower cost of ownership.

The network must be designed to provide an output brightness level increase of 1.4 for each successive brightness level. For the optimum design, the actual (or predicted) transfer curve of the CRT must be considered. The desired brightness curve is shown in Figure 4-19. The transfer function of the digital network is:

$$B = K(\sqrt{2})^n + B_o$$

where

B = display brightness

K = Mechanization constant

n = Integral video levels (0, 1, 2 . . . 15)

B_o = Minimum display brightness.

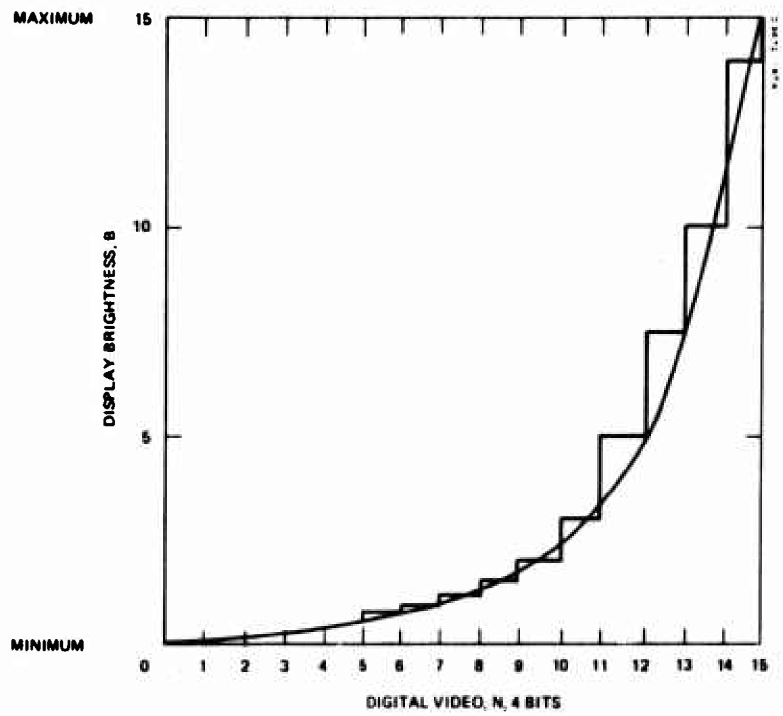


Figure 4-19. Sample of a logarithmic gamma.

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APPENDIX A. INSTRUCTIONS TO SUBJECTS

This is an experiment to find out how our ability to see patterns depends upon various viewing conditions. Specifically, two patterns will be employed in the study, one consisting of vertical lines, and one consisting of both horizontal and vertical lines crossing in such a manner as to form a pattern of squares or "patches". The size of the display you are viewing will be changed during the experiment. The spatial frequency, or number of lines making up the pattern will also be varied.

Both the line and the patch patterns are composed of black and white lines. At the beginning of each trial, there will be enough contrast on the display for you to see the pattern. You will be given a knob by which you can both increase and decrease contrast. Clockwise increases contrast; counter-clockwise decreases contrast. Your task will be to adjust the contrast on the display in order to determine two types of visual thresholds: one which we will term your "minimum detectable" threshold, the other we shall call your "100 percent" threshold.

When asked to set your minimum detectable threshold for a given condition you are to adjust the contrast on the display until you can just see that there is a pattern on the screen. In other words you should be able to see that the screen is other than a flat field and in fact you should be able to state whether the pattern you are viewing is lines or patches. However, when setting minimum detectable thresholds, it is alright if the pattern appears to fade in and out of view. We are looking for the lowest modulation setting for a given condition where you can see that there is a pattern on the display and can identify the pattern, but the pattern need not remain visually stable as you view it. You will be asked to set two minimum detectable thresholds in succession for any given condition.

Next you will be asked to set your 100 percent threshold. This is defined as the lowest modulation setting at which you can see the line or patch pattern on the display and the pattern does not fade in and out but rather remains continuously in view. For 100 percent threshold settings, if you are focused on the left side of the display the right side need not be concomitantly in focus; however, any point at which you are focused on the display must remain visible as you view it. One final caution. Prolonged starting at any one point will cause a tendency for the pattern to fade in the field of view. Try and keep your eyes moving around. You will be asked to set two 100 percent thresholds in succession for any given condition.

In setting both minimum detectable and 100 percent thresholds you may overshoot and use the control to bracket the threshold region until you are certain of your setting.

After each setting you are to hand the contrast control knob to the experimenter who will record the setting, change the knob, and then hand it back to you for your next threshold setting.

Finally, while finding your thresholds, it is necessary that you do not move your head laterally from side to side as such motion makes the pattern perception easier. Thus during trials, you will be seated 6 feet from the display and will be asked to rest your chin in a chin rest.

TABLE B-1. MODULATION THRESHOLDS IN CANDLES PER SQUARE METER

Stimulus Luminance, cd/m^2	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 15 min. Surround Luminance: 03 cd/m^2 Entries: Modulation at Threshold									
0.3	0.31377	0.14962	0.10760	0.08971	0.09497	0.12632	0.21571	0.29743	
3	0.14934	0.06667	0.04576	0.03504	0.03608	0.04541	0.07323	0.09840	0.38247
30	0.14209	0.05939	0.03890	0.02736	0.02741	0.03263	0.04970	0.06507	0.23191
300	0.27024	0.10576	0.06610	0.04272	0.04161	0.04688	0.06742	0.08603	0.28110
3,000		0.37649	0.22456	0.13329	0.12630	0.13461	0.18283	0.22736	0.68111
Subtense: 15 min. Surround Luminance: 3 cd/m^2 Entries: Modulation at Threshold									
0.3	0.57458	0.26973	0.19183	0.15673	0.16482	0.21636	0.36446	0.49946	
3	0.17481	0.07683	0.05214	0.03913	0.04003	0.04972	0.07909	0.10562	0.40215
30	0.10631	0.04375	0.02834	0.01953	0.01944	0.02284	0.03431	0.04465	0.15587
300	0.12925	0.04980	0.03078	0.01949	0.01886	0.02097	0.02975	0.03773	0.12077
3,000	0.31413	0.11331	0.06684	0.03888	0.03660	0.03849	0.05157	0.06374	0.18705
Subtense: 15 min. Surround Luminance: 30 cd/m^2 Entries: Modulation at Threshold									
0.3		0.79560	0.55955	0.44802	0.46805	0.60634			
3	0.33480	0.14486	0.09723	0.07151	0.07266	0.08906	0.13976	0.18550	0.69184
30	0.13016	0.05273	0.03377	0.02282	0.02255	0.02615	0.03876	0.05013	0.17141
300	0.10115	0.03836	0.02345	0.01455	0.01399	0.01535	0.02148	0.02708	0.08489
3,000	0.15714	0.05580	0.03255	0.01855	0.01735	0.01801	0.02380	0.02924	0.08405
Subtense: 15 min. Surround Luminance: 300 cd/m^2 Entries: Modulation at Threshold									
0.3									
3		0.44690	0.29662	0.21379	0.21582	0.26106	0.40412	0.53309	
30	0.26073	0.10398	0.06586	0.04360	0.04281	0.04900	0.07163	0.09208	0.30842
300	0.12952	0.04836	0.02923	0.01778	0.01698	0.01838	0.02538	0.03180	0.09764
3,000	0.12862	0.04496	0.02594	0.01449	0.01346	0.01379	0.01798	0.02195	0.06179
Subtense: 15 min. Surround Luminance: 3,000 cd/m^2 Entries: Modulation at Threshold									
0.3									
3									
30	0.85458	0.33549	0.21015	0.13634	0.13300	0.15021	0.21662	0.27676	0.90802
300	0.27136	0.09974	0.05962	0.03553	0.03371	0.03603	0.04906	0.06109	0.18375
3,000	0.17226	0.05928	0.03382	0.01851	0.01708	0.01727	0.02221	0.02695	0.07433

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(Table B-1, continued)

Stimulus Luminance, cd/m^2	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 30 min.	Surround Luminance: 0.3 cd/m^2					Entries: Modulation at Threshold			
0.3	0.14272	0.07921	0.06345	0.06435	0.07261	0.10972	0.21381	0.31289	
3	0.06740	0.03503	0.02678	0.02494	0.02737	0.03914	0.07202	0.10271	0.48771
30	0.06364	0.03096	0.02259	0.01933	0.02063	0.02791	0.04850	0.06741	0.29344
300	0.12010	0.05471	0.03809	0.02994	0.03108	0.03979	0.06529	0.08843	0.35294
3,000	0.45311	0.19325	0.12839	0.09269	0.09362	0.11337	0.17570	0 23189	0.84860
Subtense: 30 min.	Surround Luminance: 3 cd/m^2					Entries: Modulation at Threshold			
0.3	0.24225	0.13236	0.10485	0.10420	0.11680	0.17420	0.33485	0.48702	
3	0.07313	0.03741	0.02828	0.02582	0.02815	0.03972	0.07210	0.10220	0.47532
30	0.04414	0.02114	0.01525	0.01279	0.01356	0.01811	0.03104	0.04287	0.18281
300	0.05325	0.02388	0.01644	0.01266	0.01306	0.01650	0.02671	0.03595	0.14055
3,000	0.12841	0.05391	0.03542	0.02506	0.02515	0.03005	0.04594	0.06026	0.21602
Subtense: 30 min.	Surround Luminance: 30 cd/m^2					Entries: Modulation at Threshold			
0.3	0.67279	0.36189	0.28350	0.27609	0.30745	0.45252	0.85807		
3	0.12983	0.06539	0.04888	0.04373	0.04736	0.06596	0.11811	0.16638	0.75797
30	0.05009	0.02362	0.01685	0.01384	0.01459	0.01922	0.03250	0.04461	0.18634
300	0.03862	0.01705	0.01161	0.00876	0.00898	0.01119	0.01788	0.02391	0.09158
3,000	0.05954	0.02461	0.01599	0.01109	0.01105	0.01303	0.01965	0.02562	0.08997
Subtense: 30 min.	Surround Luminance: 300 cd/m^2					Entries: Modulation at Threshold			
0.3									
3	0.37714	0.18697	0.13823	0.12118	0.13039	0.17920	0.31655	0.44318	
30	0.09300	0.04317	0.03046	0.02452	0.02567	0.03338	0.05568	0.07596	0.31080
300	0.04584	0.01992	0.01341	0.00992	0.01010	0.01243	0.01958	0.02603	0.09764
3,000	0.04517	0.01838	0.01181	0.00802	0.00795	0.00925	0.01376	0.01783	0.06131
Subtense: 30 min.	Surround Luminance: 3,000 cd/m^2					Entries: Modulation at Threshold			
0.3									
3		0.87483	0.63960	0.54947	0.58736	0.79664			
30	0.28254	0.12911	0.09008	0.07108	0.07391	0.09484	0.15607	0.21163	0.84815
300	0.08903	0.03809	0.02536	0.01838	0.01859	0.02257	0.03508	0 04635	0.17032
3,000	0.05608	0.02246	0.01427	0.00950	0.00935	0.01074	0.01576	0.02029	0.06837

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(Table B-1, continued)

Stimulus Luminance, cd/m^2	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 1 degree	**Surround Luminance: 0.3 cd/m^2**					**Entries: Modulation at Threshold**			
0.3	0.06558	0.04237	0.03780	0.04662	0.05608	0.09628	0.21409	0.33252	
3	0.03073	0.01859	0.01583	0.01793	0.02098	0.03403	0.07156	0.10832	0.62827
30	0.02879	0.01631	0.01325	0.01379	0.01569	0.02412	0.04782	0.07054	0.37510
300	0.05392	0.02859	0.02217	0.02119	0.02346	0.03411	0.06388	0.09182	0.44769
3,000	0.20187	0.10021	0.07416	0.06512	0.07011	0.09646	0.17058	0.23894	
Subtense: 1 degree	**Surround Luminance: 30 cd/m^2**					**Entries: Modulation at Threshold**			
0.3	0.10318	0.06562	0.05790	0.06998	0.08362	0.14169	0.31079	0.47975	
3	0.03091	0.01840	0.01550	0.01721	0.02000	0.03206	0.06641	0.09990	0.56756
30	0.01851	0.01032	0.00829	0.00846	0.00956	0.01450	0.02837	0.04158	0.21661
300	0.02216	0.01157	0.00887	0.00831	0.00914	0.01311	0.02422	0.03460	0.16525
3,000	0.05303	0.02591	0.01896	0.01632	0.01745	0.02370	0.04134	0.05756	0.25202
Subtense: 1 degree	**Surround Luminance: 30 cd/m^2**					**Entries: Modulation at Threshold**			
0.3	0.26562	0.16630	0.14511	0.17188	0.20402	0.34118	0.73821		
3	0.05086	0.02982	0.02483	0.02701	0.03119	0.04935	0.10083	0.15075	0.83893
30	0.01947	0.01069	0.00849	0.00849	0.00953	0.01427	0.02753	0.04011	0.20466
300	0.01490	0.00766	0.00581	0.00533	0.00582	0.00825	0.01503	0.02133	0.09981
3,000	0.02279	0.01096	0.00793	0.00669	0.00711	0.00953	0.01639	0.02268	0.09730
Subtense: 1 degree	**Surround Luminance: 300 cd/m^2**					**Entries: Modulation at Threshold**			
0.3		0.68958	0.59504	0.69072	0.81446				
3	0.13695	0.07903	0.06508	0.06939	0.07959	0.12427	0.25049	0.37220	
30	0.03351	0.01810	0.01423	0.01393	0.01555	0.02297	0.04372	0.06330	0.31640
300	0.01639	0.00829	0.00622	0.00559	0.00607	0.00849	0.01525	0.02152	0.09863
3,000	0.01603	0.00759	0.00543	0.00449	0.00474	0.00627	0.01064	0.01463	0.06146
Subtense: 1 degree	**Surround Luminance: 3,000 cd/m^2**					**Entries: Modulation at Threshold**			
0.3									
3	0.60334	0.34274	0.27911	0.29164	0.33230	0.51208			
30	0.09437	0.05019	0.03901	0.03744	0.04149	0.06050	0.11359	0.16348	0.80033
300	0.02951	0.01469	0.01090	0.00961	0.01036	0.01429	0.02533	0.03553	0.15948
3,000	0.01844	0.00860	0.00609	0.00493	0.00517	0.00674	0.01129	0.01544	0.06353

(Continued next page)

(Table B-1, continued)

Stimulus Luminance, cd/m^2	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 2 degrees	Surround Luminance: 0.3 cd/m^2					Entries: Modulation at Threshold			
0.3	0.03044	0.02289	0.02275	0.03413	0.04375	0.08536	0.21657	0.35700	
3	0.01416	0.00997	0.00945	0.01303	0.01624	0.02998	0.07184	0.11540	0.81762
30	0.01316	0.00867	0.00785	0.00994	0.01205	0.02105	0.04763	0.07457	0.48439
300	0.02446	0.01509	0.01304	0.01516	0.01788	0.02955	0.06314	0.09632	0.57368
3,000	0.09086	0.05250	0.04327	0.04622	0.05304	0.08291	0.16730	0.24872	
Subtense: 2 degrees	Surround Luminance: 3 cd/m^2					Entries: Modulation at Threshold			
0.3	0.04440	0.03286	0.03230	0.04749	0.06048	0.11643	0.29142	0.47743	
3	0.01320	0.00915	0.00858	0.01159	0.01435	0.02614	0.06179	0.09865	0.68464
30	0.00784	0.00509	0.00455	0.00565	0.00681	0.01173	0.02619	0.04075	0.25928
300	0.00932	0.00566	0.00483	0.00551	0.00646	0.01053	0.02219	0.03364	0.19628
3,000	0.02212	0.01258	0.01026	0.01074	0.01224	0.01888	0.03759	0.05553	0.29705
Subtense: 2 degrees	Surround Luminance: 30 cd/m^2					Entries: Modulation at Threshold			
0.3	0.10594	0.07720	0.07503	0.10810	0.13677	0.25987	0.64161		
3	0.02013	0.01373	0.01274	0.01686	0.02075	0.03730	0.08696	0.13798	0.93803
30	0.00765	0.00488	0.00432	0.00526	0.00629	0.01070	0.02356	0.03643	0.22707
300	0.00581	0.00347	0.00293	0.00328	0.00381	0.00614	0.01276	0.01923	0.10988
3,000	0.00881	0.00494	0.00398	0.00408	0.00462	0.00704	0.01382	0.02029	0.10630
Subtense: 2 degrees	Surround Luminance: 300 cd/m^2					Entries: Modulation at Threshold			
0.3	0.41362	0.29673	0.28520	0.40267	0.50611	0.94901			
3	0.05024	0.03374	0.03095	0.04014	0.04907	0.08706	0.20025	0.31579	
30	0.01220	0.00767	0.00671	0.00800	0.00951	0.01597	0.03468	0.05330	0.32540
300	0.00592	0.00349	0.00291	0.00319	0.00369	0.00585	0.01201	0.01798	0.10065
3,000	0.00575	0.00317	0.00252	0.00254	0.00286	0.00429	0.00831	0.01213	0.06224
Subtense: 2 degrees	Surround Luminance: 3,000 cd/m^2					Entries: Modulation at Threshold			
0.3									
3	0.20516	0.13565	0.12305	0.15638	0.18993	0.33254	0.75448		
30	0.03184	0.01971	0.01706	0.01992	0.02353	0.03898	0.08352	0.12758	0.76295
300	0.00988	0.00573	0.00473	0.00507	0.00583	0.00914	0.01848	0.02751	0.15086
3,000	0.00613	0.00333	0.00262	0.00258	0.00289	0.00428	0.00818	0.01186	0.05963

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(Table B-1, concluded)

Stimulus Luminance, cd/m²	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 4 degrees Surround Luminance: 0.3 cd/m² Entries: Modulation at Threshold									
0.3	0.01428	0.01249	0.01383	0.02524	0.03449	0.07644	0.22132	0.38720	
3	0.00659	0.00540	0.00570	0.00956	0.01271	0.02664	0.07285	0.12420	
30	0.00608	0.00466	0.00470	0.00724	0.00936	0.01856	0.04793	0.07964	0.63193
300	0.01121	0.00805	0.00774	0.01095	0.01377	0.02586	0.06304	0.10208	0.74265
3,000	0.04131	0.02778	0.02551	0.03314	0.04053	0.07199	0.16577	0.26155	1.74469
Subtense: 4 degrees Surround Luminance: 3 cd/m² Entries: Modulation at Threshold									
0.3	0.01930	0.01663	0.01820	0.03255	0.04419	0.09665	0.27605	0.47998	
3	0.00569	0.00459	0.00480	0.00788	0.01041	0.02153	0.05808	0.09841	0.83433
30	0.00336	0.00254	0.00253	0.00381	0.00490	0.00959	0.02443	0.04034	0.31353
300	0.00396	0.00280	0.00266	0.00369	0.00461	0.00854	0.02054	0.03305	0.23553
3,000	0.00932	0.00617	0.00560	0.00713	0.00867	0.01520	0.03452	0.05413	0.35369
Subtense: 4 degrees Surround Luminance: 30 cd/m² Entries: Modulation at Threshold									
0.3	0.04269	0.03621	0.03920	0.06868	0.09263	0.19996	0.56335	0.97353	
3	0.00805	0.00639	0.00660	0.01063	0.01394	0.02848	0.07577	0.12759	
30	0.00303	0.00226	0.00222	0.00329	0.00420	0.00811	0.02037	0.03343	0.25452
300	0.00229	0.00159	0.00150	0.00203	0.00252	0.00461	0.01095	0.01751	0.12222
3,000	0.00344	0.00224	0.00201	0.00251	0.00303	0.00525	0.01176	0.01833	0.11732
Subtense: 4 degrees Surround Luminance: 300 cd/m² Entries: Modulation at Threshold									
0.3	0.15448	0.12899	0.13810	0.23714	0.31771	0.67687			
3	0.01862	0.01456	0.01487	0.02346	0.03057	0.06162	0.16172	0.27067	
30	0.00449	0.00328	0.00320	0.00464	0.00588	0.01121	0.02779	0.04533	0.33808
300	0.00216	0.00148	0.00138	0.00183	0.00226	0.00408	0.00955	0.01518	0.10377
3,000	0.00208	0.00133	0.00119	0.00145	0.00174	0.00297	0.00656	0.01016	0.06367
Subtense: 4 degrees Surround Luminance: 3,000 cd/m² Entries: Modulation at Threshold									
0.3	0.91475	0.75193	0.79609						
3	0.07048	0.05424	0.05480	0.08471	0.10967	0.21815	0.56479	0.93952	
30	0.01085	0.00782	0.00754	0.01071	0.01348	0.02538	0.06204	0.10058	0.73476
300	0.00334	0.00225	0.00207	0.00271	0.00331	0.00590	0.01362	0.02152	0.14416
3,000	0.00206	0.00130	0.00114	0.00137	0.00163	0.00274	0.00598	0.00921	0.05654

TABLE B-2. MODULATION THRESHOLDS IN FOOT LAMBERTS

Stimulus Luminance, fL	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 15 min.	Surround Luminance: 0.5 fL					Entries: Modulation at Threshold			
0.5	0.19620	0.08796	0.06054	0.04662	0.04808	0.06072	0.09827	0.13226	0.51690
5	0.11243	0.04719	0.03100	0.02192	0.02199	0.02628	0.04016	0.05268	0.18876
50	0.12878	0.05061	0.03172	0.02061	0.02011	0 02273	0.03281	0.04194	0 13779
500	0.29488	0.10850	0.06490	0.03873	0.03676	0.03932	0.05359	0.06675	0.20107
Subtense: 15 min.	Surround Luminance: 5 fL					Entries: Modulation at Threshold			
0.5	0.37171	0.16405	0.11167	0.08425	0.08633	0.10759	0.17177	0.22977	0.87961
5	0.13615	0.05626	0.03654	0.02533	0.02524	0.02976	0.04488	0.05850	0 20532
50	0.09969	0.03857	0.02391	0.01522	0.01476	0.01646	0.02344	0.02977	0.09581
500	0.14591	0.05285	0.03126	0.01828	0.01724	0.01820	0.02447	0 03029	0 08937
Subtense: 15 min.	Surround Luminance: 50 fL					Entries: Modulation at Threshold			
0.5	0.15223	0.50060	0.33698	0.24916	0.25363	0.31195	0.49129	0.65314	
5	0.26977	0.10974	0.07049	0.04788	0.04741	0.05516	0.08205	0.10629	0.36544
50	0.12626	0 04809	0.02948	0.01839	0.01771	0.01950	0.02739	0.03458	0.10900
500	0.11813	0 04212	0.02464	0.01412	0.01323	0.01378	0.01828	0.02249	0.06499
Subtense: 15 min.	Surround Luminance: 500 fL					Entries: Modulation at Threshold			
0.5									
5	0.87462	0.35024	0.22249	0.14809	0.14566	0.16728	0.24543	0.31601	1.06423
50	0.26167	0.09810	0.05947	0.03636	0.03479	0.03780	0.05237	0.06572	0.20291
500	0.15649	0.05493	0.03178	0.01785	0.01661	0.01708	0.02234	0.02732	0 07734

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(Table B-2, continued)

Stimulus Luminance, fL	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 30 min.		**Surround Luminance: 0.5 fL**				**Entries: Modulation at Threshold**			
0.5	0.08377	0.04371	0.03351	0.03138	0.03450	0.04951	0.09143	0.13060	0.62349
5	0.04763	0.02327	0.01703	0.01465	0.01566	0.02126	0.03708	0.05162	0.22593
50	0.05414	0.02476	0.01729	0.01366	0.01421	0.01825	0.03006	0.04078	0.16366
500	0.12301	0.05268	0.03510	0.02548	0.02578	0.03132	0.04872	0.06441	0.23698
Subtense: 30 min.		**Surround Luminance: 5 fL**				**Entries: Modulation at Threshold**			
0.5	0.14710	0.07557	0.05729	0.05258	0.05743	0.08132	0.14814	0.21031	0.98347
5	0.05347	0.02571	0.01861	0.01568	0.01666	0.02232	0.03840	0.05313	0.22780
50	0.03885	0.01749	0.01208	0.00935	0.00966	0.01225	0.01990	0.02683	0.10548
500	0.05642	0.02379	0.01567	0.01115	0.01121	0.01344	0.02062	0.02709	0.09763
Subtense: 30 min.		**Surround Luminance: 50 fL**				**Entries: Modulation at Threshold**			
0.5	0.42267	0.21374	0.16026	0.14413	0.15638	0.21853	0.39273	0.55412	
5	0.09820	0.04649	0.03327	0.02748	0.02900	0.03835	0.06508	0.08948	0.37581
50	0.04561	0.02022	0.01380	0.01048	0.01075	0.01345	0.02156	0.02889	0.11123
500	0.04234	0.01757	0.01145	0.00798	0.00797	0.00943	0.01428	0.01864	0.06581
Subtense: 30 min.		**Surround Luminance: 500 fL**				**Entries: Modulation at Threshold**			
0.5		0.98922	0.73349	0.64644	0.69680	0.96095			
5	0.29510	0.13754	0.09733	0.07879	0.08261	0.10779	0.18045	0.24660	
50	0.08761	0.03823	0.02582	0.01920	0.01958	0.02417	0.03821	0.05089	0.19193
500	0.05199	0.02124	0.01369	0.00935	0.00928	0.01083	0.01617	0.02099	0.07259

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(Table B-2, continued)

Stimulus Luminance, fL	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 1 degree		Surround Luminance: 0.5 fL				Entries: Modulation at Threshold			
0.5	0.03613	0.02194	0.01874	0.02135	0.02502	0.04078	0.08594	0 13028	0.75977
5	0.02039	0.01159	0.00945	0.00988	0.01127	0.01738	0.03458	0.05109	0.27319
50	0.02299	0.01224	0.00952	0.00915	0.01015	0.01480	0.02782	0.04006	0.1963[illegible]
500	0.05184	0.02584	0.01918	0.01693	0.01826	0.02521	0.04474	0.06278	0.28216
Subtense: 1 degree		Surround Luminance: 5 fL				Entries: Modulation at Threshold			
0.5	0.05881	0.03516	0.02970	0.03315	0.03859	0.06208	0.12906	0.19446	
5	0.02121	0 01187	0.00957	0.00981	0.01111	0.01691	0.03320	0.04875	0.25532
50	0.01529	0.00802	0.00616	0.00581	0.00639	0.00921	0.01707	0.02443	0.11731
500	0.02204	0.01082	0.00794	0.00687	0.00736	0.01002	0.01755	0.02447	0.10775
Subtense: 1 degree		Surround Luminance: 50 fL				Entries: Modulation at Threshold			
0.5	0.15663	0.09220	0.07700	0.08422	0.09741	0.15466	0.31715	0.47493	
5	0.03611	0.01990	0.01586	0.01594	0.01793	0.02693	0.05215	0.07611	0.39044
50	0.01664	0.00859	0.00653	0.00603	0.00660	0.00937	0.01714	0.02438	0.11467
500	0.01533	0.00741	0.00538	0.00456	0.00485	0.00652	0.01126	0.01561	0.06733
Subtense: 1 degree		Surround Luminance: 500 fL				Entries: Modulation at Threshold			
0.5	0.68257	0.39551	0.32665	0.35015	0.40231	0.63038			
5	0.10059	0.05457	0.04301	0.04236	0.04733	0.07016	0.13404	0 19440	0.97692
50	0.02963	0.01505	0.01132	0.01024	0.01113	0.01561	0.02816	0.03981	0.18341
500	0.01745	0.00830	0.00596	0.00495	0.00523	0.00694	0.01183	0.01629	0.06883

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(Table B-2, continued)

Stimulus Luminance, fL	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 2 degrees			**Surround Luminance: 0.5 fL**			**Entries: Modulation at Threshold**			
0.5	0.01574	0.01113	0.01059	0.01467	0.01832	0.03393	0.08160	0.13129	0.93531
5	0.00881	0.00583	0.00530	0.00674	0.00819	0.01435	0.03259	0.05109	0.33372
50	0.00987	0.00611	0.00530	0.00619	0.00732	0.01213	0.02601	0.03975	0.23803
500	0.02207	0.01281	0.01059	0.01137	0.01307	0.02050	0.04151	0.06181	0.33939
Subtense: 2 degrees			**Surround Luminance: 5 fL**			**Entries: Modulation at Threshold**			
0.5	0.02375	0.01653	0.01555	0.02111	0.02620	0.04789	0.11359	0.18165	
5	0.00850	0.00554	0.00497	0.00620	0.00748	0.01294	0.02900	0.04519	0.28910
50	0.00608	0.00371	0.00318	0.00364	0.00427	0.00699	0.01480	0.02247	0.13181
500	0.00870	0.00497	0.00406	0.00427	0.00488	0.00756	0.01509	0.02234	0.12013
Subtense: 2 degrees			**Surround Luminance: 50 fL**			**Entries: Modulation at Threshold**			
0.5	0.05864	0.04017	0.03737	0.04972	0.06130	0.11057	0.25874	0.41122	
5	0.01341	0.00860	0.00764	0.00934	0.01119	0.01911	0.04222	0.06539	0.40979
50	0.00613	0.00368	0.00312	0.00350	0.00409	0.00660	0.01377	0.02079	0.11943
500	0.00561	0.00315	0.00255	0.00263	0.00298	0.00456	0.00898	0.01321	0.06958
Subtense: 2 degrees			**Surround Luminance: 500 fL**			**Entries: Modulation at Threshold**			
0.5	0.23686	0.15975	0.14696	0.19161	0.23466	0.41776	0.96431		
5	0.03464	0.02187	0.01920	0.02300	0.02739	0.04614	0.10058	0.15482	0.95040
50	0.01013	0.00599	0.00502	0.00552	0.00639	0.01019	0.02097	0.03146	0.17705
500	0.00592	0.00328	0.00262	0.00265	0.00298	0.00450	0.00874	0.01278	0.06594

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(Table B-2, concluded)

Stimulus Luminance, fL	Spatial Frequency, Cycles/Degree								
	2	3	4	6-3/4	8	11-1/4	16	18-3/4	32
Subtense: 4 degrees Surround Luminance: 0.5 fL Entries: Modulation at Threshold									
0.5	0.00693	0.00570	0.00604	0.01018	0.01356	0.02853	0.07827	0.13367	
5	0.00385	0.00297	0.00300	0.00464	0.00601	0.01197	0.03102	0.05162	0.41183
50	0.00428	0.00308	0.00298	0.00423	0.00533	0.01004	0.02457	0.03985	0.29148
500	0.00949	0.00641	0.00590	0.00771	0.00945	0.01684	0.03891	0.06149	0.41241
Subtense: 4 degrees Surround Luminance: 5 fL Entries: Modulation at Threshold									
0.5	0.00969	0.00785	0.00823	0.01358	0.01797	0.03731	0.10100	0.17142	
5	0.00344	0.00261	0.00261	0.00396	0.00509	0.01001	0.02558	0.04231	0.33070
50	0.00244	0.00174	0.00166	0.00231	0.00289	0.00537	0.01295	0.02088	0.14962
500	0.00347	0.00231	0.00210	0.00269	0.00327	0.00575	0.01311	0.02060	0.13531
Subtense: 4 degrees Surround Luminance: 50 fL Entries: Modulation at Threshold									
0.5	0.02218	0.01769	0.01832	0.02965	0.03897	0.07986	0.21325	0.35970	
5	0.00503	0.00376	0.00372	0.00552	0.00706	0.01369	0.03453	0.05676	0.43450
50	0.00228	0.00160	0.00151	0.00206	0.00256	0.00469	0.01118	0.01790	0.12565
500	0.00207	0.00136	0.00122	0.00153	0.00185	0.00322	0.00723	0.01129	0.07264
Subtense: 4 degrees Surround Luminance: 500 fL Entries: Modulation at Threshold									
0.5	0.08304	0.06519	0.06679	0.10592	0.13827	0.27969	0.73668		
5	0.01205	0.00886	0.00866	0.01261	0.01602	0.03065	0.07625	0.12456	0.93407
50	0.00350	0.00241	0.00224	0.00300	0.00371	0.00672	0.01578	0.02512	0.17267
500	0.00203	0.00131	0.00116	0.00143	0.00172	0.00294	0.00652	0.01012	0.06381